UNCLASSIFIED

PRESSURE-THRUST RELATIONSHIPS OF VISCO-ELASTIC FLUIDS

FINAL REPORT

Covering The Period

April 8 - December 31, 1963

Contract No: DA 18-108-AMC-130 (A)

DA Project No: IC 522 301 A 065

(4C-09-04-006)

RMD Project No. 5513

Thiokol®

CHEMICAL CORPORATION

REACTION MOTORS DIVISION

DENVILLE, NEW JERSEY

THIOKOL CHEMICAL CORPORATION
Reaction Motors Division
Denville, New Jersey

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February 5, 1964

Thiokol
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5513-F

PRESSURE-THRUST RELATIONSHIPS OF VISCO-ELASTIC FLUIDS

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Abstract

Existing portable flamethrowers use thickened visco-elastic fuels which are expelled by gas pressure usually obtained from high pressure ambient temperature storage bottles. Maximum effective range of these devices is between 45 and 55 meters under ideal conditions. It is desirable to increase range substantially in order to increase weapon effectiveness and decrease operator vulnerability.

The means of attaining greater range is well known: basically, larger expulsion nozzle diameter is mandatory, with equivalent or higher expulsion velocity (perhaps with other peripheral system modifications). Since fuel flow rate increases roughly with the square of the nozzle diameter, and linearly with velocity, fuel tank volume for even short firing times (e.g., 5 seconds) increases very rapidly. The weight and bulk of the associated high pressure gas reservoirs therefore become equivalently larger, and further increases result from the demand for higher fuel pressures. Expulsion recoil is nearly proportional to mass flow rate, hence almost immediately becomes uncontrollable for a man-held expulsion device.

Based upon a series of theoretical and experimental programs performed previously by Thiokol Chemical Corporation, Reaction Motors Division, for Edgewood Arsenal, and upon their own technical studies, CRDL of Edgewood Arsenal had assembled an Experimental Flamethrower Research Device for exploration of possible flamethrower improvements. This device consisted of a 10-gal fuel tank connected by a flexible hose to a recoil-compensated flame gun. Counterrecoil thrust was provided by a liquid bipropellant rocket engine which had been fabricated by RMD; however, a means of pressurization was not included. Under this contract, RMD was to develop a promising controllable pressurization source--presumably a gas generator using liquid bipropellants (which had been shown in earlier studies to be most feasible) to provide hot, high-pressure gas; and then to evaluate the performance of the complete system with special attention to the synchronization of transient phenomena. The goal was to obtain an insight into the feasibility of a man-portable long-range recoil-compensated flamethrower pressurized by combustion processes.

Very early in this program, an alternative configuration was developed for a recoil-compensated flamethrower which offered many advantages over the concept embodied in the Flamethrower Research Device. This alternative was a single-shot model which consisted of a 3-gal fuel tank with an attached solid propellant rocket which provided both counterrecoil thrust and pressurization for fuel expulsion. The inherent simplicity and reliability of solid propellant actuation, coupled with extremely economical construction and an estimated operational prototype weight of less than 30 lb, compared very favorably with the 100-pound-plus multi-shot unit.

Authorization was given to investigate both versions of the recoil-compensated flamethrower--in effect, to conduct two parallel, essentially separate programs. Necessarily, each was somewhat curtailed in comparison with the program which had been envisioned for evaluation of the original concept alone. For convenience, the two systems will be referred to as the liquid propellant flamethrower (LP F/T) and solid propellant flamethrower (SP F/T), respectively.

A diversified test program was performed with each of the systems in order to characterize operating parameters, integrate components, evaluate the overall assemblies, and explore various functional options. Some difficulties were encountered, as in any program; specifically, thrust measurement posed problems, and gel rod integrity (which was not a responsibility under this contract) left much to be desired. However, both test efforts were highly successful in demonstrating reliable, predictable operation of each assembly under nearly any practical set of conditions desired. Recoil compensation was shown to be feasible in both the LP F/T and the SP F/T, and adequate synchronization of counterrecoil with expulsion recoil forces was demonstrated. Noteworthy in the LP F/T tests were: the highly dependable capability to restart the LP gas generator against backpressures of over 500 psig; operation of the N_2O_4/UDMH gas generator at oxidizer/fuel ratios between 0.035 and 0.50, to provide pressurization by gases with measured temperatures between 250 and 730 F. Outstanding accomplishments in the SP F/T effort were: simultaneous rocket compensation of recoil and pressurized expulsion of flame fuel by a single solid propellant grain; utilization of a small aluminized solid propellant grain for ignition of the heavily-thickened fuel, in place of hypergolic ignition by means of chromyl nitrate (a reactive liquid which poses handling and storage problems); more than adequate rod ignition by this solid propellant technique of gels stored in an unprotected SP F/T at temperatures down to 0° F; and maximum fuel deposition ranges up to 160 yards from the firing point, in spite of unfavorable rod behavior.

It was concluded (at least on the basis of very limited familiarity with battlefield conditions) that while the multi-shot LP F/T was entirely feasible technically, it would result inevitably in a system too heavy to be practical for a man-portable device, and that its multi-shot capability offered no significant advantage over an equivalent number of shots from one-shot SP F/T's. However, the LP gas generator appeared to offer a highly desirable replacement for the large compressed air storage flasks of mechanized flamethrowers. The greatest boon of such a substitution, aside from obvious large reductions in weight and volume, would be elimination of the requirement for auxiliary air compressors and long charging times needed to reload these high pressure reservoirs. Another application of the LP gas generator would be for dissemination of CW/BW agents.

On the other hand, it was demonstrated that the SP F/T can provide a simple, low-cost, lightweight recoil-compensated device capable of firing a single quantity of thickened fuel to ranges two to three times those attainable with existing portable flamethrowers. It was indicated that in production quantities, a 3-gal SP F/T containing 19 lb of fuel could weigh 27-30 lb complete and cost appreciably less than $50 each, whether fabricated from steel, aluminum, or fiberglass-reinforced plastic. Nearly every major function of the combat model has been demonstrated successfully; and those few functions not proven all are well within the present state-of-the-art.

Immediate development is recommended for this weapon, which would provide the infantry, air assault troops, and Marines with a highly flexible, mobile, compact weapon. It will greatly reduce the vulnerability of the operator, significantly increase his effectiveness, permit the use of flame against many targets now inaccessible--and accomplish all this with reduced weight and cost, and increased reliability.

In support of this development, work should be initiated to obtain fuel rods from the prototype which are essentially intact to ranges of 100 yards or more. Such rods have been obtained repeatedly from mechanized flamethrowers, hence there is good reason to be confident that they can be achieved without excessive difficulty in the operational SP F/T.

Figure 1. Solid Propellant-Actuated, Recoil Compensated, One-Shot Long-Range Flamethrower in Operation

1.0 INTRODUCTION

The thickened gasoline fuel used in existing portable flamethrowers is at present pressurized in most cases by cold compressed gas stored in a high pressure tank carried with the flamethrower. The effective range for these devices is between 45 and 55 meters under ideal conditions. From a tactical standpoint, it is desirable to increase this range substantially in order to increase the effectiveness of the weapon and to reduce the vulnerability of the operator.

Several problems arise, however, as the range of a multiple-shot flamethrower is increased. First, the size and weight of the device, of which the cold gas pressurization system is a significant portion, become substantially larger. Second, the increases in rod diameter and velocity of the thickened fuel required to achieve the increased range results in a significant increase in recoil, making control of a hand-held weapon difficult if not impossible. Third, the increased concentration of thickener required reduces the volatility of the fuel and renders the present pyrotechnic match igniters unreliable.

Technical studies have been performed by Thiokol Chemical Corporation, Reaction Motors Division, under Contract DA18-108-405-CML-891 to investigate the feasibility of utilizing combustion processes for pressurization of visco-elastic fluids, and to provide recoil compensation for the thrust produced by ejection of the visco-elastic fluids from the flamethrower. This study concluded that the use of combustion processes would make it possible to replace cold gas reservoirs with smaller and lighter pressurization apparatus and to provide recoil compensation. Subsequently, under Contract CP2--11983-c, Reaction Motors Division fabricated a nominal 100-lb thrust bipropellant rocket engine for incorporation into the Flamethrower Research Device constructed by CRDL at Edgewood Arsenal.

At its inception, the present program was modeled around the Flamethrower Research Device which was a government-furnished item for this program. This unit (which is described in detail in Section 2 below) consisted basically of a 10-gal flamethrower fuel tank connected by means of a high-pressure hose to an experimental recoil-compensated flame gun. The flame gun was mounted in a thrust-measuring framework which was installed on a machine-gun tripod. This unit was capable of single- or multiple-shot operation, but lacked a source of pressurization. Ignition of the fuel rod was accomplished hypergolically by the use of chromyl nitrate expelled from a hypodermic needle by a separate motorized device.

One of the major tasks of this effort was to select the most promising means of pressurizing the 10-gal fuel tank. As a result of the theoretical studies performed under the first of the two previous contracts cited above, pressurization by means of hot combustion gases was selected for investigation. From the earlier work, a liquid bipropellant gas generator utilizing nitrogen tetroxide (N_2O_4) and unsymmetrical dimethylhydrazine (UDMH) as oxidizer and fuel, respectively, was chosen as being representative

of a class of controllable-output hot gas pressure sources. After separate development and checkout, this gas generator was to be coupled to the Flamethrower Research Device to permit experimental evaluation of the complete system.

Very early in this present program, extensive effort was devoted to finding possibilities for simplifying and lightening the conceptual multiple-shot long range flamethrower. This effort culminated in the evolution of an alternative configuration for a recoil-compensated flamethrower which offered many advantages. This alternate model consisted of a 3-gal fuel tank with an attached solid propellant rocket which provided both counter-recoil thrust and pressurization for flame fuel expulsion; this device afforded only single-shot operation. The inherent simplicity and reliability of solid propellant actuation, coupled with extremely economical construction and an estimated operational prototype weight of less than 30 pounds, offered an extremely attractive alternate to the 100-pound-plus multiple-shot unit. When this concept (which is described in detail in Section 3 below) was presented to contract project officials, authorization was given to investigate both the liquid propellant- and solid propellant-actuated versions of the long range recoil-compensated flamethrower.

Thus this contract resulted in the performance of two parallel, essentially separate programs. Necessarily, each of these programs was somewhat curtailed in comparison with the type of program which would have been conducted for either system individually. However, both programs produced results which clearly indicate the areas of most promising application for each of the concepts investigated. The development and testing of each of the two systems are discussed below in separate sections in order to provide the most coherent presentation, except for those aspects common to both systems. These common areas include fuel rod characteristics and thrust measurement. The flame weapons test range where these devices were evaluated also is described briefly below.

The conclusions which were reached as a result of this effort are presented in Section 7 and are followed by recommendations for the best application of each of these systems.

2.0 LIQUID PROPELLANT-ACTUATED RECOIL-COMPENSATED FLAMETHROWER

The two basic approaches selected for the study of the pressure-thrust relationships of visco-elastic fluids for the purpose of advancing the state-of-art in connection with longer range portable flamethrowers are discussed in the Introduction. As indicated in that section, these methods include the multi-shot liquid propellant-actuated recoil-compensated flamethrower and the single-shot solid propellant-actuated recoil-compensated flamethrower. The factors influencing the selection of the liquid flamethrower system, design studies leading to the selection, and the experimental results of this phase of the program will be discussed in this section.

Briefly, this portion of the program included:

a) Continuation of the theoretical studies previously conducted under Contract DA 18-108-405-CML-891 for the purpose of studying the physical parameters involved in the gas pressurization of a visco-elastic fluid (thickened gasoline) for a flamethrower having a fluid mass flow rate of about 12.5 lbs/second through a 0.5 in. diameter nozzle.

b) Selection of a means of pressurizing the thickened gasoline based on the above theoretical considerations.

c) Experimental confirmation of the assumed parameters by the design, fabrication and testing of the selected pressurization method, and,

d) Integration of the pressurization system into the government-furnished Flamethrower Research Device for breadboard feasibility tests of the selected method of thickened gasoline pressurization and recoil compensation.

The government-furnished Flamethrower Research Device consisted essentially of the following components:

1. A flamethrower gun assembly consisting of a contoured discharge nozzle having a 0.5 inch diameter throat and a two inch pneumatically operated ball valve for on-off flow control of the thickened gasoline (gelgas).

2. A ten-gallon capacity gelgas tank 8 inches in diameter and approximately 66 inches long containing a sliding piston to separate the pressurizing gas from the gelgas. A 10 foot long, 1.3 inch ID flexible hose connected the gelgas tank to the flamethrower gun assembly.

3. A bipropellant recoil-compensating rocket designed for a nominal thrust level of 100 lb. This rocket, mounted on the flamethrower gun in line with, but directly opposed to the gelgas nozzle was designed, fabricated, tested and delivered to Edgewood Arsenal for this purpose by Reaction Motors under Contract CP2-11983-c. The counter recoil rocket is discussed in detail in Section 2.4.

4. A chemical ignition system consisting of an electrical motor driving a rod through a flexible shaft. The rod advanced the plunger of a hypodermic syringe which ejected a liquid in a fine stream.

5. Associated tankage, valves and controls for operation of the counter recoil rocket, a pressurization source, the ignition system and the flamethrower gun valve.

The flamethrower gun, including the recoil rocket was mounted on a machine gun tripod mount providing for adjustment in elevation and azimuth of the flamethrower. The installation also included provisions for measuring recoil and counter recoil forces.

Although the bipropellant recoil rocket had not been operated in conjunction with the flamethrower gun at Edgewood Arsenal, tests at that facility had demonstrated the feasibility of compensating for the recoil with such a rocket device using compressed air as the working fluid. At the outset of this program, therefore, the major task to be accomplished was the development of a combustion gas pressurization system suitable for the unique duty cycle of a multi-shot flamethrower. With this accomplished, the analytical studies indicated that the pressurization source and the counter recoil rocket could be integrated into a breadboard unit to demonstrate the feasibility of the concept and provide the quantitative data necessary for the design and development of a prototype unit.

The steps taken to accomplish these objectives are discussed in the following paragraphs.

2.1 Summary of Analytical Studies

Tests conducted at the Chemical Research and Development Laboratories of the Edgewood Arsenal in Maryland demonstrated that ranges in excess of 100 yards could be obtained with the Flamethrower Research Device at a thickened gasoline flowrate of 12.5 lb/sec using a 0.5 inch diameter nozzle. These tests were made with cold gas pressurization of the fuel tank. Based on empirical data from these tests, it was determined that a fuel tank pressure of approximately 450 psi is required for maximum range with this configuration and the recoil or reverse thrust due to expulsion of the thickened gasoline is about 90 lbs. For a desired firing time of 5 seconds, a fuel supply of about 10 gal was implied.

Based on these empirical data, Thiokol-RMD conducted theoretical studies under Contract DA18-108-405-CML-891 to investigate the parameters affecting gas pressurization of thickened gasoline and for providing recoil compensation. As part of this study various techniques for pressurization and recoil compensation were considered. Some of these methods included (a) compressed gas and liquefied gas systems, (b) solid propellant combustion systems, (c) hybrid (liquid and solid) combustion systems, (d) monopropellant systems, and (e) bipropellant combustion systems. It was readily shown in the study that those systems employing hot gases for pressurization of the thickened gasoline and recoil compensation present the greatest advantages in that weight and size are minimized. In order to select the best overall system for development, however, other considerations such as controllability, reliability, safety, simplicity, and logistics had to be weighed against size and weight.

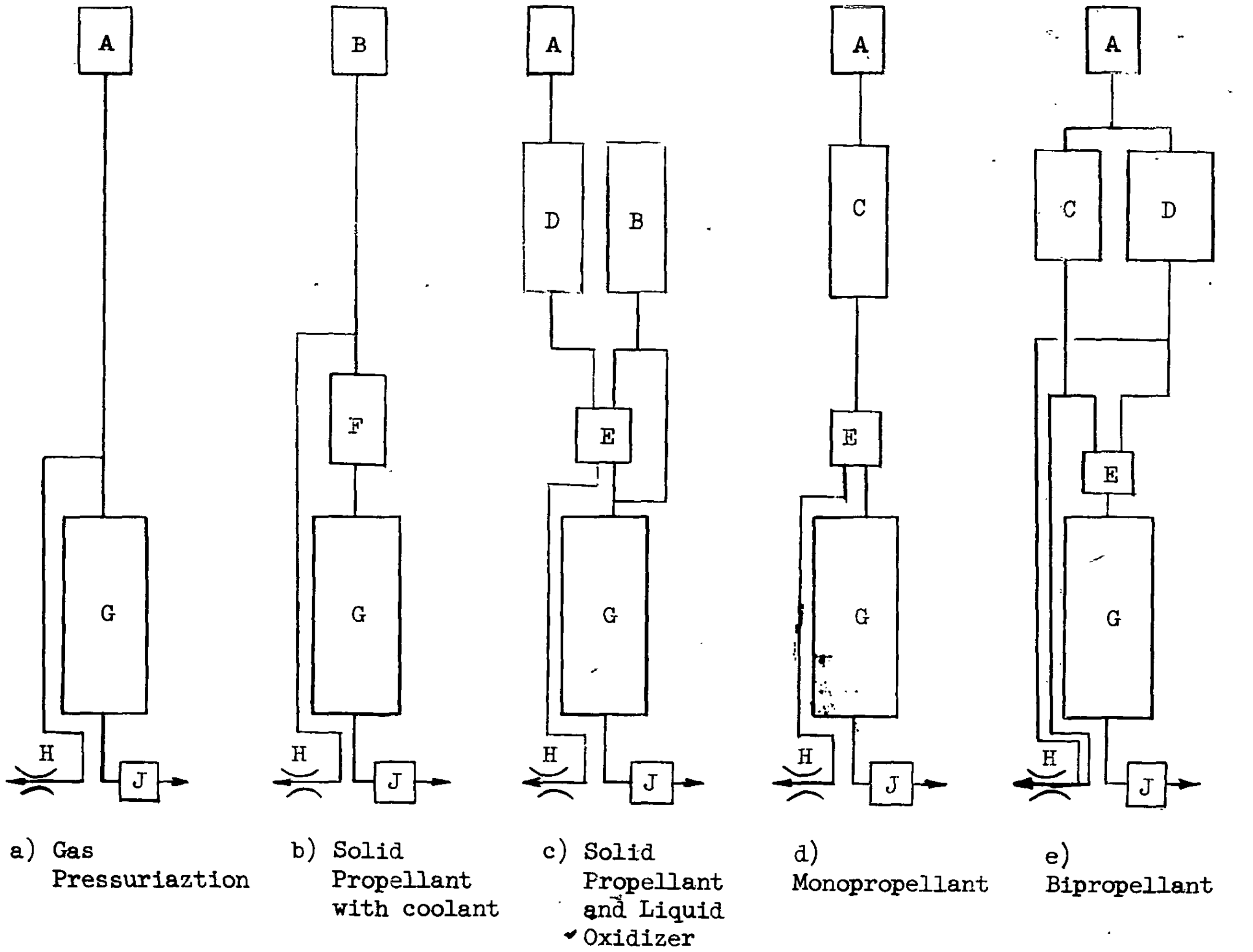
Typical system configurations considered in the previous study of various techniques for pressurization and recoil compensation are shown schematically in Figure 2. Some of the pertinent characteristics of these configurations are presented in Table I. Included in this table are working fluids typical of each configuration, values for these theoretical operating temperatures and performance, and an indication of the relative utility of the various working fluids and system configurations based on cost, control, weight and logistics.

Briefly, the major advantages and disadvantages of the systems which were studied and are shown schematically in Figure 2 may be summarized as follows:

a) Compressed gas system - This is the system currently used. It is a simple, reliable and easily serviceable system (assuming availability of a suitable compressor in the field) but its size and weight, particularly with recoil compensation provisions, are substantially greater than those systems employing combustion processes. The increased gas requirements make the compressed gas system impractical for a portable weapon having the desired 10-gal fuel capacity.

b) Solid propellant system - Considering its small size, weight, and relative simplicity, the solid propellant concept is potentially an advantageous system. Its major disadvantage is that multiple charges are necessary to provide for intermittent (short burst) operation since solid grains are not well suited for repeated start-stop operation. It is probably also necessary to cool the gases used to pressurize the gasoline.

c) Hybrid systems - This concept does not appear suitable for the flamethrower application at the present time since techniques for hybrid combustion processes are not as well developed as those for other combustion processes. The hybrid system has



A - Compressed N_2 or air
B - Fuel-rich solid propellant
C - Liquid propellant fuel or monopropellant
D - Liquid propellant oxidizer or monopropellant
E - Combustion chamber
F - Coolant
G - Thickened fuel
H - Reverse thrust rocket
J - Fuel gun with igniter

Figure 2

Comparison of Various Flamethrower System Configurations

TABLE I - CHARACTERISTICS OF THE VARIOUS PRESSURIZATION AND REVERSE THRUST CONFIGURATIONS SHOWN IN FIGURE 2

	SYSTEM	WORKING FLUID CHARACTERISTICS			COMMENTS				
No.	Title	Source	T_c (°R)	I_{sp}, sec	Cost	Control	Weight	Field Supply	Field Handling
a	Gas Pressurization	Compressed Nitrogen or Air	520	---	low	easy	very high	excellent	excellent
	Liquid	Carbon Dioxide	351	---	low	easy	medium	good	good
	Pressurant	Freon 22 ($CHClF_2$)	420	---	high	easy	medium	poor	good
b	Solid	AP Composite	4000(1)	220	low	difficult	low	good	good
	Propellant	Double Base	4000(1)	220	low	difficult	low	good	good
c	Solid Propellant and Liquid	AP Composite + H_2O_2	5000	250	medium	difficult	low	medium	poor
	Oxidizer	+ N_2O_4	5000	250	medium	difficult	low	medium	poor
d	Monopropellant	Hydrogen Peroxide	1840	133			low	poor	poor
	or Fuel System	Propyl Nitrate	2345	179	high	medium	low	poor	good
		Hydrazine	1585	174	high	medium	low	poor	good
		Gasoline + Air	4000(3)	240	low	medium	low	good	good
		Propane + Air	4000	240	low	medium	low	good	good
e	Bipropellant	Gasoline + H_2O_2	5150	235	medium	medium	low	poor	poor
	System	NH_3 + MON(2)	4700	238	high	medium	low	poor	poor
		N_2H_4 + N_2O_4	5350	238	medium	medium	low	poor	poor

(1) Coolant used for pressurization either ammonium oxalate or similar diluent.
(2) Mixed Oxides of Nitrogen.
(3) Estimated

essentially the same disadvantages as the solid propellant grain. It is not suitable for on-off operation unless very reactive oxidizers are employed.

d) Monopropellant systems - Except for hydrogen peroxide which has storability limitations, monopropellants do not appear to be suitable for this application. Although relatively simple since only one propellant system is involved, and field handling and servicing are simplified, most monopropellants require an ignition source (igniter, catalyst bed, etc.) and some require relatively large combustion chambers. Most monopropellants also tend to be shock and/or heat sensitive, making their use more hazardous for this application due to the intimate proximity to the operator.

e) Bipropellant system - This system combines the advantages of minimum size and weight with rocket combustion technology in which the state of the art is well advanced. Ignition systems are not required with hypergolic propellants. Its problem areas are common with any system selected in that proper synchronization of the recoil rocket with the flamethrower is required.

Since synchronization of the pressurization-flamethrower-recoil compensation functions is of prime importance and also provides the major problem area, controllability (transient characteristics, repeatability, reliability, etc.) was a major deciding factor in the final selection of the pressurization method. For simplicity, it would be desirable to use a single gas generating device for both the pressurization and the recoil compensation requirements. Several problems associated with this concept, however, made it more practical to utilize separate sources for these functions. First, a low temperature gas is desirable for pressurization while a high temperature gas is desirable for the recoil rocket in order to obtain reasonable efficiency. Secondly, the action of the recoil rocket must be initiated by, or synchronized with, the ejection of fuel from the flamethrower nozzle. The ejection of the fuel, however, depends upon prior pressurization of the thickened gasoline tank. The functions of recoil compensation and pressurization, therefore, cannot be provided simultaneously by a single source. While neither of these problems present insurmountable difficulties, separate devices for pressurization and recoil compensation presented the optimum solution. Several types of fuel tank pressurization systems with characteristics compatible with the overall systems discussed above were considered.

On the basis of these brief comparisons it appeared that the bipropellant liquid combustion system and the solid propellant combustion system merited further study. The bipropellant liquid system had the advantage of greater flexibility for the multi-shot application, however, the inherent simplicity of the solid propellant system (if the control problems could be overcome) was obviously attractive. With the conception of the one-shot solid

propellant flamethrower with its consequent solid grain and coolant bed development, simultaneous work on a solid propellant system development directed toward a multi-shot, 10 gallon system was not practical within the scope of this program. The bipropellant liquid system using the same hypergolic propellant combination for both the pressurization and the counter-recoil rocket functions was selected as the most practical approach for multi-shot investigations.

2.2 Propellant Selection

Many monopropellants, bipropellants and solid propellants can be used for pressurization purposes. The selection of the propellants and the pressurization system, of course, is dependent upon the specific application. The reasons for selecting a liquid bipropellant system have already been discussed. Propellants suitable for a large single-shot booster engine are not necessarily suitable for a space engine requiring restart capability. Similarly, the requirements for the long range portable flamethrower application are considerably different in many respects from the rocket propulsion field. It is necessary, therefore, to consider the specific requirements of the proposed long range multi-shot, portable flamethrower application. Propellant characteristics considered necessary for the accomplishment of the test program and for possible application in quantity production, field-use equipment were:

a) Stability and physical properties - Long term storage in portable tanks and standard supply facilities is a necessity for ultimate field-use. Compatible materials of construction, sealing and lubricating materials must be available for the range of temperatures to be encountered. Desirable properties are low freezing point, high boiling point, high density, and low viscosity.

b) Hypergolicity - Desirable to minimize ignition requirements for both the counter recoil rocket and the gas generator. Pyrotechnics, catalysts or other ignition devices are undesirable from the standpoint of simplicity, reliability and servicing requirements.

c) Handling and Safety Considerations - Although prepackaging techniques rather than field servicing are expected to be used, handling and safety requirements must be compatible with field use conditions. The possibility of system leaks or tank ruptures due to handling or battle field damage must be considered. Pyrophoric, toxic, or highly corrosive propellants are obviously undesirable and should not be used.

d) Thermodynamic performance - Reasonably high performance, that is--pounds of thrust or cu.ft. of hot gas per pound of propellant--is desirable in order to minimize the weight and size of the propellant system for the counter recoil rocket and the gas generator.

These characteristics define the criteria for selecting propellants suitable for portable flamethrowers. The development of extended storage capability requirements for some missile applications has led to the packageable propellant concept. Packageable propellants can be stored for long periods of time at ambient temperatures without significant loss of materials and can be hermetically sealed for periods up to 5 years in tanks with a minimum vapor space.

Propellants meeting these requirements therefore must be thermally stable at ambient temperatures. The existence of such propellants has made possible the development of prepackaged liquid rocket engines that can be filled with propellant at the production facility, sealed and stored for subsequent use. Similar storability requirements are anticipated for the flamethrower application. The use of the packaged liquid concept for the flamethrower will permit the loading of tanks or containers in central supply facilities for delivery to battle areas thus minimizing logistics problems and eliminating problems associated with filling in the field.

A number of propellants meet the packageability requirements. Some of these are chlorine trifluoride, nitrogen tetroxide, and nitric acid for oxidizers and the hydrazine-based fuels such as unsymmetrical dimethyl hydrazine, monomethyl hydrazine and blends with hydrazine. Chlorine trifluoride is not considered applicable for this application because of its extreme reactivity and toxicity. The thermal sensitivity of neat hydrazine rules it out as a fuel although the hydrazine-based fuels are suitable in this regard. The more conventional fuels such as gasoline and the kerosenes (RP and JP's) are not suitable because they are not hypergolic with the acceptable oxidizers. Most of the other available rocket oxidizers and fuels were excluded after due consideration due to vapor pressure, toxic, corrosive, pyrophoric or safety characteristics incompatible with this application.

Because of the general suitability of UDMH and N_2O_4, this combination was selected for use in this program. Possible improvements in physical properties can be made by slight propellant modification. For example, the freezing point of N_2O_4 is +13.6° F. Although this is not suitable for field use, the addition of 25% NO depresses the freezing point to -65° F without materially affecting its operational characteristics. The freezing and boiling points of UDMH are -71° F and 146° F respectively and are suitable for most geographic locations and service requirements. All subsequent tests were made with these propellants except for one series of gas generator tests in which monomethyl hydrazine was used in place of UDMH in order to compare operational characteristics.

2.3 Gas Generator Development Program

As indicated in the previous sections, most bipropellant combinations can be used to generate gases for pressurization purposes by using an off-stoichiometric mixture ratio to obtain gas temperatures in the desired range. For this program, N_2O_4 and UDMH were selected, for both the recoil compensating rocket and the pressurization system. While these propellants may be operated either fuel-rich or oxidizer-rich, fuel-rich operation for the gas generator was selected in order to ensure compatibility with the structural materials and the gelled gasoline. Fuel-rich gases are also generally of lower molecular weight since oxidizer-rich gases may consist largely of O_2, N_2, CO_2 and oxides of nitrogen. The weight of propellant required to produce a given volume of gas at a given pressure would be less if the combustion took place at a fuel-rich mixture ratio.

Combustion gas temperature less than about 1200°F was desired in order to preclude potential structural problems in the gas generator and gelgas tank as well as compatibility problems with the gelled gasoline. Previous experience at Reaction Motors indicated that this was entirely feasible with the selected propellant combination. Stable operation and reliable ignition had been demonstrated with a generator operating at a mixture ratio (O/F) of 0.08 which produced gas temperatures of about 1000°F.

2.3.1 The Portable Flamethrower Gas Generator Concept

The function of the gas generator is to provide a means of pressurizing the gel storage tank and to maintain the pressure at the desired level during gel expulsions. Another possible function could be to provide small quantities of high pressure gases for auxiliary purposes such as flamethrower and recoil rocket valve actuation. Although solenoid valves were used for these functions in the breadboard feasibility study device, it is probable that mechanical or pneumatically actuated controls would be developed for the field unit.

With the selection of a bipropellant pressurization system for the multi-shot flamethrower studies, several possible liquid gas generator designs had to be considered. For example, the gas generator could be operated as a simple rocket motor, exhausting the hot combustion gases through a conventional rocket nozzle into the gas side of the gelgas tank. In this case, the gas generator operates at essentially constant chamber pressure determined by propellant flowrate and nozzle throat size, except of course during the starting and stopping transients. The pressure in the gelgas tank would increase during operation until it reached gas generator chamber pressure, where it would be maintained during expulsion.

Another alternative was to eliminate the nozzle or orifice between the gas generator and the gelgas tank. With this configuration, the pressure in both the generator and the gelgas tank would be essentially the same during both the transient and the steady-state periods of operation. Insofar as overall system operation was concerned, either configuration was satisfactory. The elimination of the nozzle would facilitate

fabrication, however, it remained to be determined if generator operation would be stable if the nozzle were not employed. Since bipropellant gas generators have been used successfully for a wide range of pressure and flow conditions for other applications, no stability problems were anticipated in this application.

One further advantage of not employing the nozzle between the generator and gelgas tank, permitting generator chamber pressure to vary with gelgas tank pressure, is the possibility of affecting propellant flowrates to the generator during the transient period in order to reach operating pressure more quickly than would be possible with the constant chamber pressure, constant flowrate configuration. Since flowrate is a function of pressure drop between the propellant tank pressures and chamber pressure (assuming venturi flow control is not employed in a field unit), the propellant flowrate will be greatest when the chamber pressure is low. Thus, during transient periods when chamber pressure is increasing, the time to reach the desired pressure can be shortened by the higher propellant flowrate to the gas generator.

2.3.2 Experimental Hardware and Control Systems

This section describes the components comprising the liquid propellant gas generator including the alternative experimental hardware. The two primary methods of controlling the GG will then be discussed. Subsequent sections will describe test results obtained using the components in each mode of operation.

Figure 3 is a schematic diagram of the complete flamethrower system. Minor modification of the control circuits permitted automatic operation in any of the modes which are described later. The system and controls also permitted either the gas generator or the recoil rocket to be operated independently so that their individual characteristics could be determined and modified as desired.

Figure 4 shows the details of the gas generator combustion chamber, the double impinging stream injector and the method of mounting to an accumulator which was used in the initial tests of the government-furnished Research Flamethrower Device.

Gas Generator

The nominal design parameters for the gas generator shown in Figure 4 are summarized below:

Chamber pressure, psia	450
Chamber diameter, in.	1.10
Chamber length, in.	1.90
Nozzle diameter, in. (when used)	.154
Characteristic length, L*, in. (when nozzle used)	100
Fuel flowrate, lb/sec	.185
Oxidizer flowrate, lb/sec	.015
Mixture ratio, O/F	.081

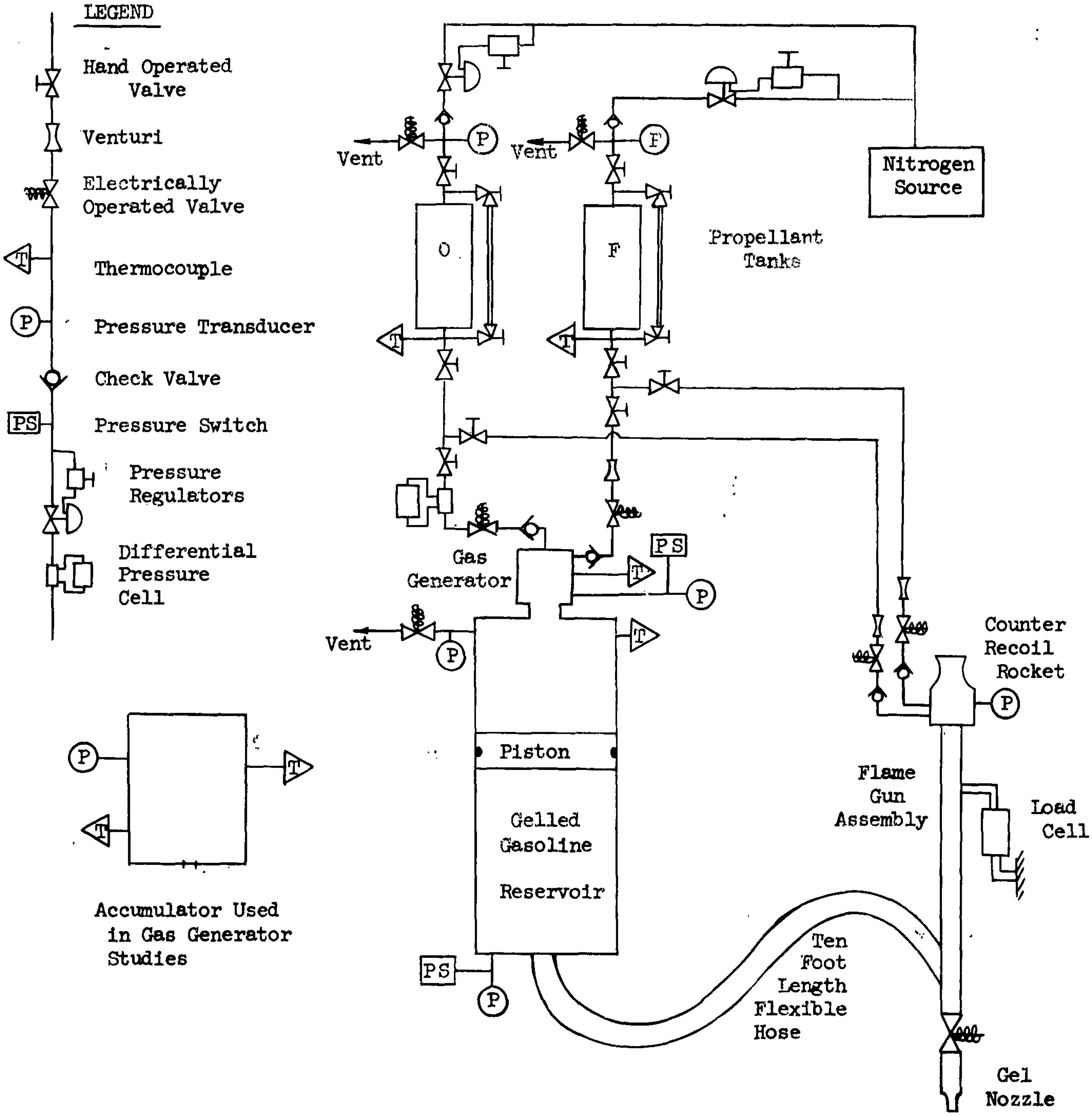


Figure 3. Experimental Liquid Propellant Flamethrower

Schematic Diagram

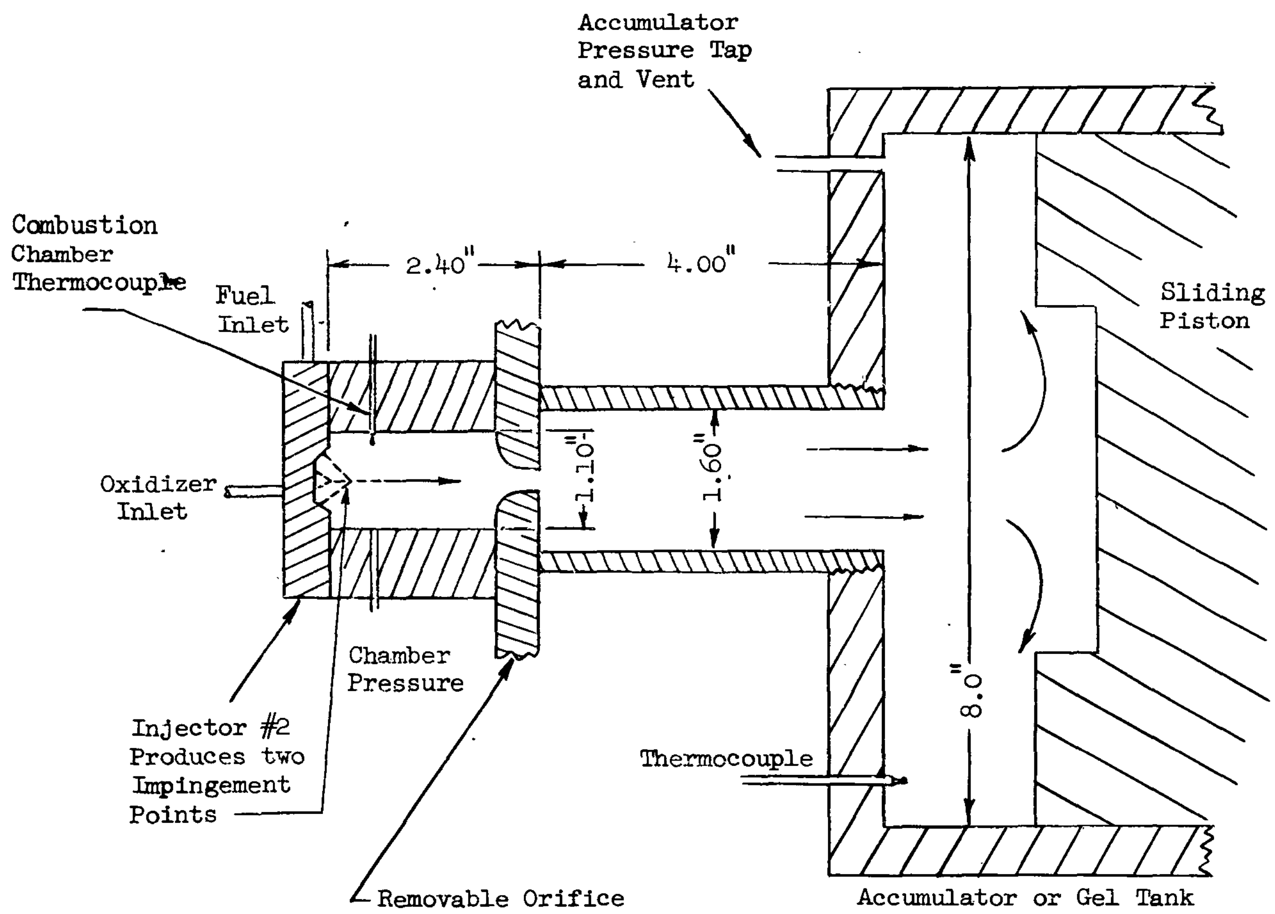


Figure 4. Experimental Liquid Propellant - Actuated Flamethrower Gas Generator

The gas generator chamber was fabricated from copper.

Two injectors were designed and fabricated for the experimental program. The first injector was a simple impinging stream injector. It consisted of four fuel streams impinging on a single oxidizer stream at a point about 0.3 in. from the injector face. Although theoretical calculations indicated that there should be no liquid species formed even at the extremely fuel-rich mixture ratios, the attainment of these products depends upon proper mixing by the injector. In anticipation of possible injector modifications to ensure adequate mixing, a second injector was desinged and fabricated. This injector, shown in Figure 4, employed a double impingement pattern. One fuel stream and one oxidizer stream impinged at a point relatively close to the injector face at a mixture ratio close to optimum. Four additional fuel streams then impinged at a point further downstream. The purpose of this design was to establish combustion at a more conventional mixture ratio and then add the remainder of the fuel to obtain the desired temperature.

Control Systems

As indicated previously, several methods of controlling gas generator operation to provide pressurization for the flamethrower duty cycle were considered. In one such method, the gas generator would be operated only when it was desired to expel the gel. This would result in "minimum energy" operation since generator operation would be limited only to actual flamethrower actuation, except for the time necessary to reach operating pressure. Another method of operation would permit the gas generator to be operated for an indefinite period in anticipation of firing the flamethrower instantly and would not require the transient period necessary to reach normal operating pressures as in the case of the "minimum energy" operation.

Basically, it is only necessary to pressurize the gel at those times when it is desired to expel gel. In the case of the minimum energy system, however, a finite time of generator operation is required to raise the pressure to the necessary level of 450 psi with an almost empty gel tank having a large gas volume or ullage, and starting at low or ambient pressure. Figure 5 shows the time required to reach 450 psi as a function of the gas volume in the Research Flamethrower Device. In the case of a ten-gallon ullage volume and at gas generator flowrates suited for the one-half inch gel nozzle, the gas generator must operate for four seconds to increase the pressure from 0 to 450 psig. This, of course, is the limiting case for the 10-gal flamethrower under consideration since a smaller ullage and/or higher starting pressure will result in shorter gas generator operating times to reach 450 psig.

The importance of this time delay is dependent on the tactical situation. If the operator has fired several bursts and has a large gas volume tc pressurize, he has the option of not firing the remainder of his gel, and

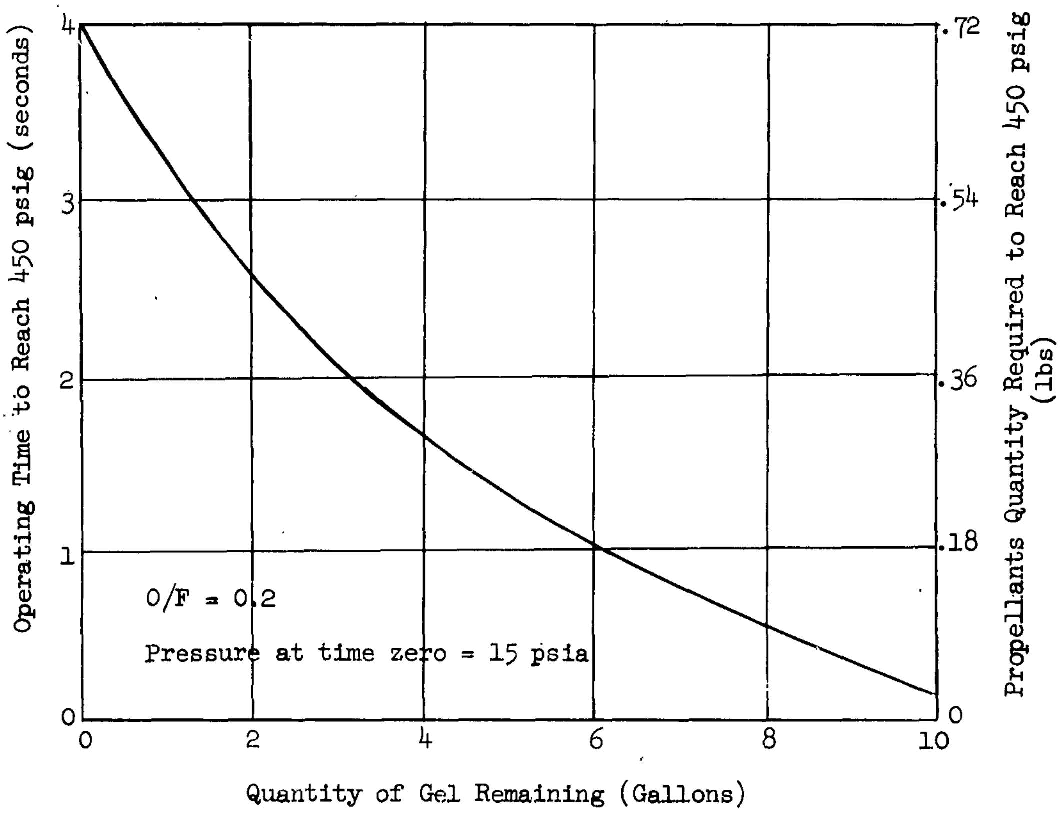


Figure 5. Gas Generator Operating Time and Propellant Requirements to Obtain System Pressure of 450 psig as a Function of the Quantity of Gel Remaining in the Research Flamethrower Device

refilling his tank or, realizing that an appreciable time delay in reaching a sufficiently high pressure level will occur, make the necessary allowance in firing his next burst. Thus, the delay need not present a hazard to the operator as long as he is aware of the condition.

If it is desirable to have immediate gel expulsion capability, an automatic control system which will maintain a system pressure of 450 psig is possible. Thus, regardless of the ullage, there will be almost no time delay in initiating gel expulsion. One method of providing "instant readiness" operation is by maintaining a system pressure at operating level by pressure switch sensing and control. If electrically operated valves are used to control the flow of propellant to the gas generator, the valves can be energized through the pressure switch contacts. If the pressure is lower than the switch setting, the propellant valves will be energized, permitting propellant flow to the combustion chamber. When the set pressure is reached, the pressure switch actuates, and the propellant valves are de-energized to shut off the propellant flow to the generator. Thus, the system pressure is maintained between limits imposed by the pressure switch actuation and deactuation pressure settings.

The potential disadvantage to the use of this system is the large quantity of propellants which may be required due to indiscriminant use of the generator. Curves are presented in Section 2.3.4 showing the propellant quantity required for various tactical needs.

The pressure switch serves as a safety device, however, since it terminates gas generator operation when the maximum pressure is reached, preventing possible overpressurization. A pressure switch was used in each of the liquid propellant tests, therefore, regardless of whether the "minimum energy" or the "instant readiness" type of operation was being evaluated. No malfunctions due to excessive pressures occurred during the testing program.

2.3.3 Gas Generator Tests

In the initial gas generator tests, the gas generator was operated as a separate unit. The combustion gases were exhausted to atmosphere through a nozzle so that the combustion process in the chamber was independent of the external conditions. The purpose of these tests was to determine steady-state operating characteristics and the relationships between flowrate, mixture ratio, chamber pressure, nozzle size, combustion chamber and efficiency. These data are summarized in Table II, Runs 5AX 5119-5143. The specific purpose and the results of each test are included.

These tests were made with the first injector design consisting of the four fuel streams impinging upon the single oxidizer stream. Although ignition was satisfactory and operation stable, the combustion gas temperature was lower than expected for the corresponding mixture ratios. Mixture ratios were

varied from 0.059 to about 0.2 with little significant effect on temperature. The low temperatures are primarily attributed to a liquid film on the thermocouple junctions due to the fuel-rich operation.

A cavitating venturi was used to control and measure fuel flowrates. Because of the extremely low oxidizer flowrates at the lower mixture ratios, a venturi was not used in the oxidizer system. Instead, a differential pressure orifice meter was used in the initial tests. Thus, oxidizer flowrate varied with chamber pressure. When chamber pressure was low, the oxidizer flowrate was high. As chamber pressure increased, the oxidizer flowrate approached the design value. Starting transients, therefore, were minimized in duration.

Following these tests, the gas generator was attached to a 225 cu. in. accumulator to determine its operating characteristics under simulated flamethrower conditions. The results of these tests are summarized in Table II, Runs 5AX5155-5196. Initially, an orifice was installed between the gas generator and the accumulator.

Following Run 5AX5157, the orifice was removed. Since operation was completely satisfactory, the intermediate orifice was not used in subsequent tests with the government-furnished Flamethrower Research Device. Combustion gas temperatures were higher in both the gas generator and in the accumulator than were measured in the gas generator tests alone, indicating that reaction was continuing downstream of the gas generator.

The exhaust orifice in the accumulator was varied to determine gas generator operation over a wide range of accumulator pressures. In Runs 5AX5168-69 the accumulator was pressurized to approximately 500 psi to determine gas generator starting characteristics against high back pressures. Ignition and operation were completely satisfactory. With the demonstration of satisfactory starting against backpressure, a pressure switch was installed on the accumulator to control gas generator operation in order to check out automatic control of accumulator pressure. Two different pressure switches and various orifices on the accumulator outlet were used to simulate the anticipated flamethrower conditions. With the demonstration of satisfactory automatic operation, it was felt that the gas generator system was ready for installation on the government-furnished Flamethrower Research Device.

The next step, then involved attaching the gas generator to the government-furnished Flamethrower Research Device and expelling water to check out the complete pressurization system operation. The results of these tests are summarized in Table III. Tests were made with separate and simultaneous operation of both the gas generator and the recoil compensating rocket. The system was completely instrumented and thrust measurements on the flamethrower were made in each direction. A limited series of tests were also made using monomethylhydrazine instead of UDMH.

System operation was satisfactory and the unit was installed in the flamethrower range for gelled gasoline expulsion tests. These tests are described in Section 2.5. Before discussing the results of the recoil rocket and expulsion tests, however, some of the significant gas generator operation and control aspects will be discussed.

2.3.4. Temperature Relations

Temperature measurements in the combustion chamber using the double impinging injector indicated that temperature varied almost linearly with mixture ratio. Figure 6 shows combustion chamber gas temperatures as a function of mixture ratio for three configurations; the gas generator operating under steady state conditions with the double impinging injector, a gas generator with vortex injection (from a previous program) and data for a gas generator with undefined operating characteristics taken from Koelle, Handbook of Astronautical Engineering, Fig. 20-103. Variations between curves are due to different injector designs, their effect on combustion efficiency which is proportional to $(T/M)^{1/2}$, and the location of the thermocouple junction in any given design.

For a ten-gallon flamethrower, the maximum continuous steady-state operating time is about five seconds for "minimum energy" system. The maximum temperature measured in the combustion gas portion of the Research Flamethrower Device was 730°F while most runs had lower temperatures.

The selection of propellant mixture ratio is thus not necessarily governed by heating rate considerations in the tank and lowest mixture ratio, lowest combustion temperatures are not necessarily required for minimum-energy operation, permitting a wide flexibility in permissible gas generator characteristics.

The cycling or "instant-readiness" mode of operation is considerably different with regard to temperature and heat transfer conditions. Remotely controlled solenoid valves with electrical power interrupted by the normally closed contacts of a pressure switch represent the easiest method of control operation and was the basic method used in this test program for this type of operation. As indicated previously, two pressure switches were used. The switches had different deadbands (difference in pressures between switch actuation during increasing pressure and subsequent de-actuation with decreasing pressure). This value determines the range in which the switch can maintain pressure in a system. The first pressure switch had a 60 psi actuation differential under slowly varying pressures while the actuation differential for the second switch was 9 psi. Because of the slow response of the pressure switch, the pressure variations controlled by the pressure switches was dependent on the rate of pressure rise (tank ullage) and in any case was larger than the nominal differentials noted above.

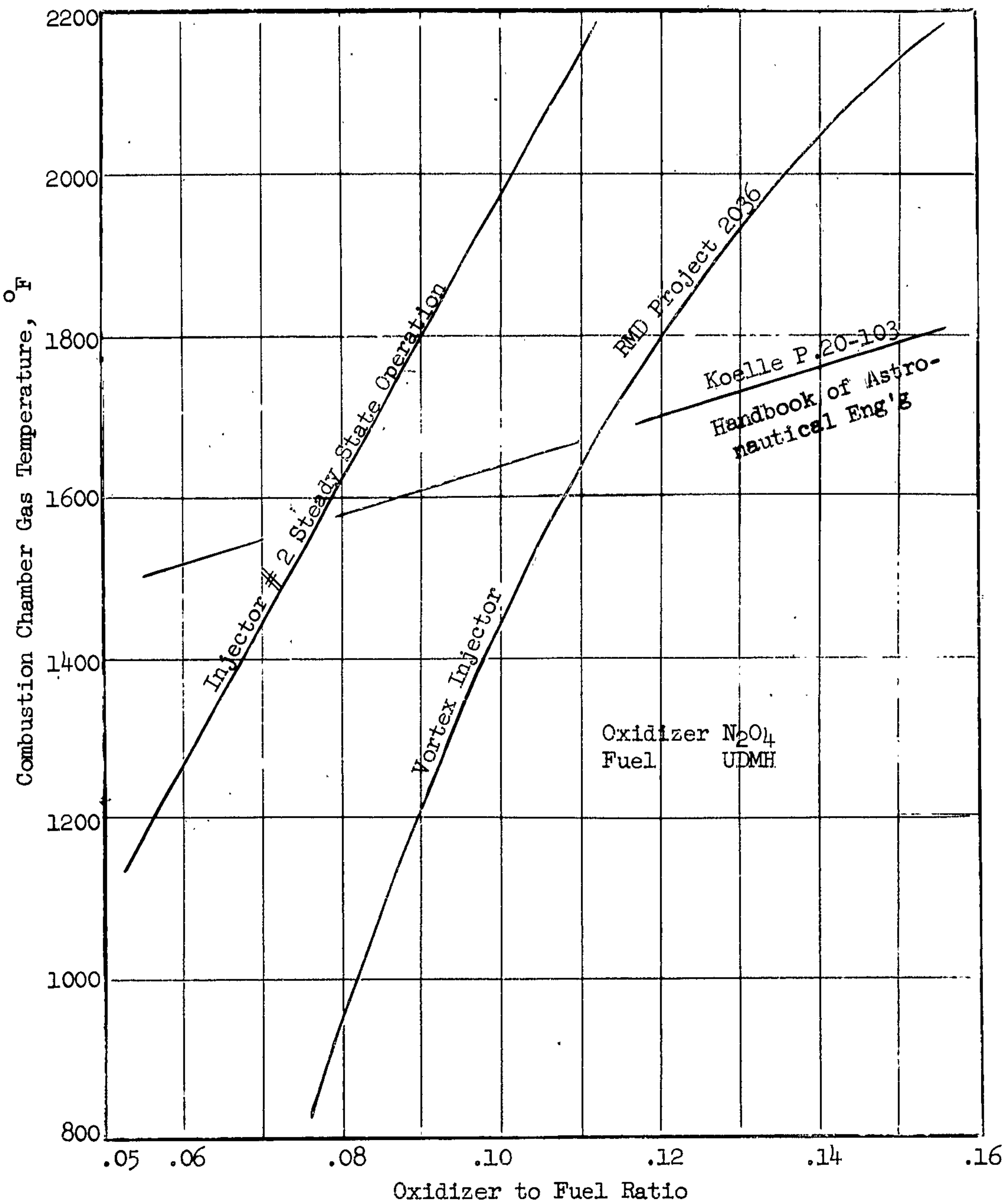


Figure 6. Combustion Chamber Temperature as a Function of O/F for Several Gas Generators Using N_2O_4/UDMH

For the 9 psi differential pressure switch, Figure 7 shows the time variation of pressure and two temperatures, using the cycling or "Instant Readiness" mode of operation. At time t = 4 seconds, operation was initiated. In a few milliseconds, the pressure increased over 500 psi, the pressure switch automatically actuated, and the gas generator propellant valves were de-energized, stopping the gas generator. The lower curve indicates that a gas generator chamber temperature of 500°F was reached (the indicated temperature is a function of the thermocouple response time). Similarly, the center curve shows that 400°F was the maximum recorded in the geltank during the initial pulse. Immediately after gas generator shutoff, the combustion gases cooled and the pressure decayed until the lower pressure switch limit was reached, at which time the gas generator valves were energized. The gas generator then fired briefly increasing the pressure and temperature until the upper pressure switch limit was again reached. The cycling continued with a total pressure variation of 70 psi for this particular condition. If a pressure switch with a faster response were used, this variation could be reduced. The cycling operation was continued until t = 63 seconds with the frequency at that time down to about 1 pulse in 10 seconds. Both the chamber gas temperature and the geltank gas temperature were reduced to 160°F.

A gel burst of two seconds duration was initiated at t = 63 seconds. With the gas volume increasing, the gas generator was required to operate for a longer duration, resulting in a higher chamber temperature indication. Since the rate of gas pressure increase is so rapid and the rate at which gel starts to flow is relatively slow, the gas generator cycled during initial gel expulsion. It can be seen from the upper trace that gel pressure varied from 410 to 450 psi during the first expulsion burst. The maximum chamber temperature recorded was 980°F while the maximum geltank gas temperature was 470°F and was not reached until t = 75 seconds. Immediately after the two second gel burst, cycling operation took place between 485 and 450 psig. With the gel tank approximately one-half empty, the rate of pressure increase is not nearly as rapid and pressure switch response time is of lesser importance.

At time t = 128 seconds, gas generator operation was stopped for 26 seconds permitting cooling of the combustion chamber and geltank as shown by the lower gas temperature curves. The geltank gas was vented down to 265 psig and subsequent pressure drop occurred due to cooling.

At t = 154 seconds, gas generator cycling was initiated with starting characteristics similar to the start at t = 4 seconds. The gel pressure increased from 256 psig to 480 psig in a fraction of a second.

The remaining gel was expelled at t = 190 seconds in an approximately three-second burst. Thus, at t = 193 the gel was expended and gel tank pressure dropped to zero. The maximum gas temperature recorded during this period was 1470°F in the gas generator chamber and 480°F in the geltank.

Gas generator operation was stopped at t = 205 seconds.

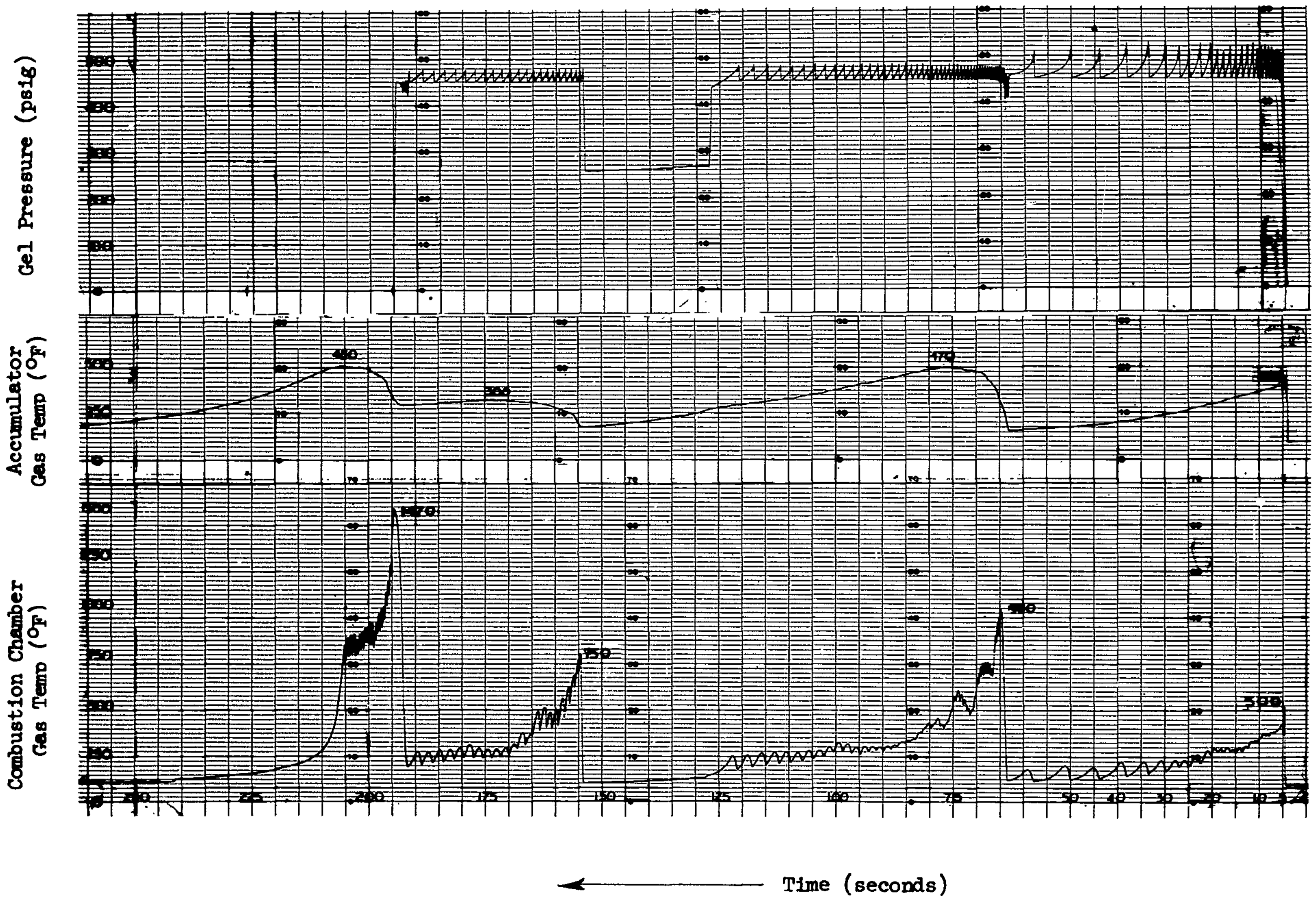


Figure 7 Recorded Traces of Pressure, Temperature, Time Relationships for Instant Readiness Operation of the Liquid Propellant-Actuated Flamethrower

Since the operation of instant-readiness control is infinitely variable in duration and in number of gel bursts, quantitative data on gel tank surface temperatures were not taken for various operating conditions. However, immediately after one test of six-minute duration in which tank pressure was maintained for two minutes before each of three gel bursts, the gel tank could not be touched for a distance of about 12 inches from the gas generator end indicating a surface temperature greater than 120° F. The gel outlet end of the tank was only slightly above ambient temperature.

2.3.5 Propellant Requirements

The quantities of gas generator propellant required for the two methods of operation previously described differ greatly from one another.

For a ten-gallon system, the number of bursts that can be made is limited to about five. Since the gas generator operates only during gel expulsion for the minimum energy method, the required propellant quantity can be calculated readily. To provide a five-burst capability, starting from ambient pressure and expelling the gel at 450 psi, approximately 10.5 seconds of total operating time is required (using Figure 5). Based on a nominal flow rate of 0.19 pounds per second (including a safety factor), 2.0 pounds of propellants are required per 10-gallon gel charge.

For the "instant readiness" type of operation, no ideal quantity of propellants can be determined which will cover all possible situations. However, Figures 5 and 8 can be used to determine the amounts required for any given tactical situation. Figure 5 shows the required propellant quantities to reach 450 psig while Figure 8 shows the propellant quantities required to maintain this pressure.

For example, the required quantity of propellants to expel ten gallons of gel in five equal bursts with a 30-second pressurization period preceding each burst is given below.

With 10 gallons of gel in the tank, .02 lbs is required to pressurize, .30 lbs is required to maintain this pressure for 30 seconds and .18 lbs is required for the one-second, two-gallon burst for a total of .50 lbs.

The corresponding weights for the remaining volumes are:

Quantity of Gel Remaining	Quantity to Pressure	Quantity to Maintain Pressure	Quantity For Expulsion	Total Quantity of Propellants Required
10 gals	.02	.30	.18	.50
8	.09	.44	.18	.71
6	.16	.58	.18	.92
4	.30	.72	.18	1.20
2	.50	.89	.18	1.57
				4.90 Total Weight

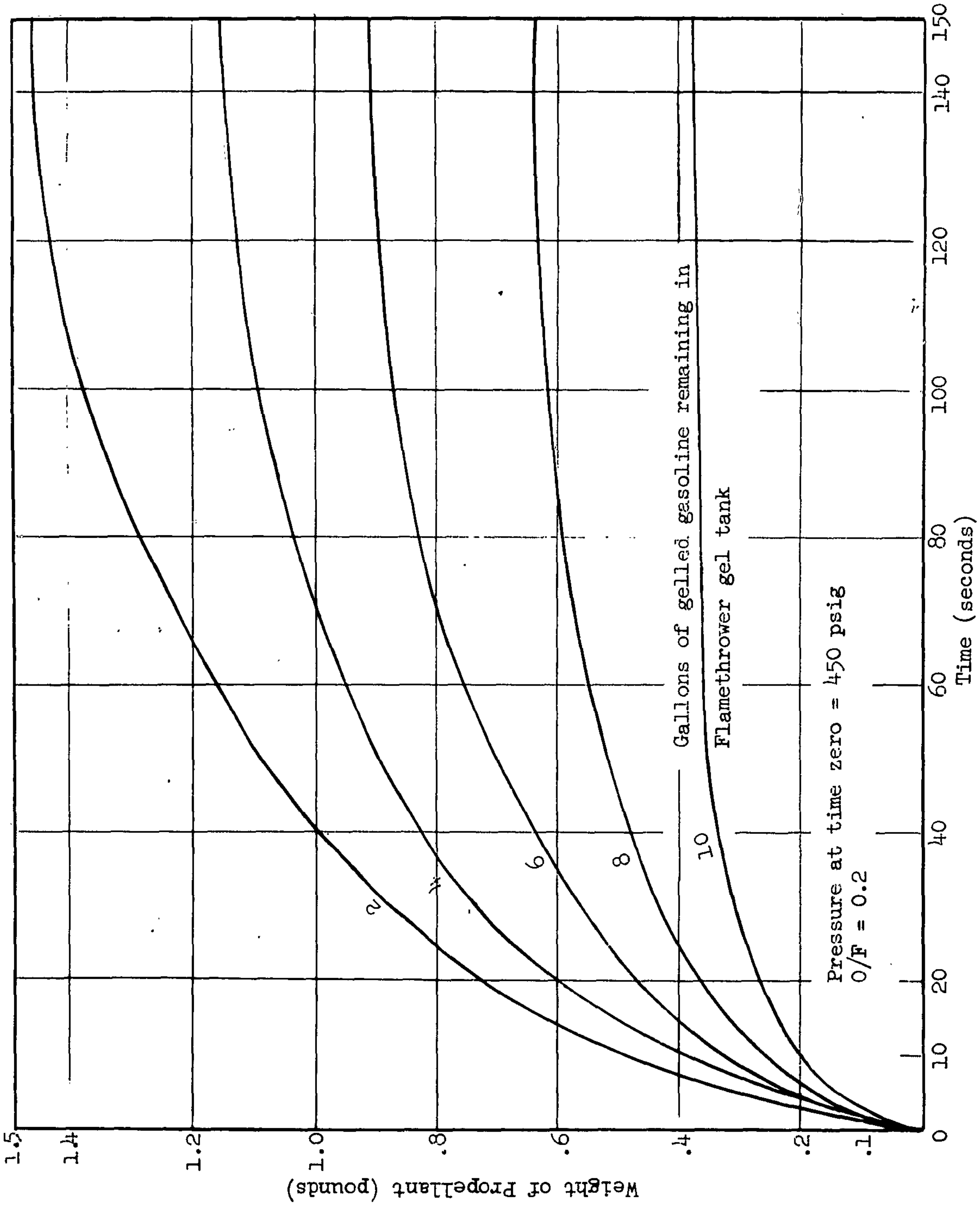


Figure 8. Weight of Propellant Required to Maintain 450 psig as a Function of Time and Volume for the Instant Readiness Mode of Liquid Propellant Gas Generator Operation

Thus, the instantaneous firing ability results in doubling the fuel requirements for short period use and even greater requirements for longer period application.

The 450 psi pressurizing gas required from the gas generator can be supplied by propellants at various mixture ratios and combustion temperatures. In the fuel-rich operating regime, the combustion temperature increases as the mixture ratio increases (Figure 6). As the combustion temperature is increased, the mass flow required to produce a given volume at 450 psi decreases. The energy losses due to heat transfer to the chamber walls and due to cooling of the walls will result in a pressure decrease.

The conflicting requirements for cool combustion products to minimize heat transfer (and possible operational problems) and hot combustion products to minimize propellant requirements, would indicate that perhaps an optimum operating temperature exists. In the many tests made, however, it was found that there was no sharply defined optimum condition. The test program covered mixture ratios from .035-.50 with satisfactory ignition and combustion characteristics in all cases. While precise flow rate measurements and hardware surface temperature measurements were not made, in each case the data in general indicate that no peak operating condition exists. With total flow rate variations from .138 to .198 lb/sec, it was noted that operating characteristics from test to test did not vary greatly. Precise control of flow rate, mixture ratio and timing is not necessary for completely satisfactory gas generator operation and variations over fairly wide ranges have little effect on overall characteristics. A minimum propellant flow rate is required, however, at each gas temperature to maintain gas pressure during gel flow conditions.

2.3.6 Combustion Product Composition

The exhaust products produced by the injectors and the simple cylindrical combustion chamber appeared to indicate incomplete propellant mixing and combustion in the gas generator although ignition was reliable and satisfactory.

In gas generator tests with the accumulator exhausting to the atmosphere and with the government-furnished Flamethrower Research Device, condensed and non-evaporated species were noted in each test. The amount of residue was reduced at higher O/F's, however. Analysis of a liquid sample showed that it was predominantly fuel (UDMH) with small amounts of water and oxidation products present.

Theoretically, liquid species should not exist in the combustion products. Although it is possible that more complicated injectors or gas generators might minimize the amount of residue accumulated, it is questionable if this added complication is warranted. No difficulties were experienced due to the residue in any of the tests. The condensate was simply drained from the gas side of the geltank after each test and no harmful or corrosive effects were noted.

Attempts to separate the gas phase from other possible phases present in the exhaust products for analysis using a centrifugal separator were not successful. The separator used consisted of a three-inch diameter stainless steel container with a tangential entry and an axial exit. Solid and/or liquid particles should coat the walls while the gases escaped through the axial outlet. Although small quantities of carbon were collected when the separator was attached to a side outlet of the accumulator, no other residue was evident. Attaching the separator directly to the gas generator also did not result in the collection of any residues.

An analysis of the gaseous combustion products was made of three tests at different mixture ratios under steady state operating conditions. A comparison of the experimental and theoretical results is shown in Table IV. It can be seen that they compare closely except for the experimental findings of ethane and propane which are not predicted theoretically.

2.4 Counter Recoil Rocket Characteristics

Based on analyses of system requirements made under Contract DA18-108-405-CML-891, a recoil compensating rocket was designed to produce a nominal thrust of 100 pounds. The counter recoil rocket (CRR) was fabricated and tested at Reaction Motors Division to assure satisfactory operation and delivered to the Army Chemical Center, Edgewood, Maryland. There, the rocket was incorporated in the workhorse Flamethrower Research Device which was sent to TCC-RMD for use under the present contract.

The following sections will review the preliminary design parameters and the rocket's characteristics in the flamethrower system, including transient analysis and test results. Discussion of thrust matching with the flamethrower recoil will be presented in Section 2.5, "Gel Expulsion Tests".

2.4.1. Thrust Chamber Design

In accordance with the Flamethrower Research Device system requirements provided by the Chemical Research and Development Laboratory, the CRR was designed for use with nitrogen tetroxide and unsymmetrical dimethylhydrazine for the reasons delineated previously. Other propellant combinations having the same general characteristics such as N_2O_4-MAF (mixed amine fuels) or IRFNA-MMH (monomethylhydrazine) also can be used. Selection of a propellant combination which is hypergolic assured a system of minimum complication. Operation of the rocket consists only of opening and closing the propellant valves, although experimental systems utilized purges and had provisions for loading, draining and checkouts to facilitate the experimental program.

Pertinent rocket engine design parameters are listed in Table V.

The thrust can be adjusted within limits by controlling the propellant flow rate through adjustment of propellant tank pressures or by changing flow metering devices. Cavitating venturis were used since they provide positive

TABLE IV

COMPARISON OF THEORETICAL COMBUSTION PRODUCT COMPOSITION WITH EXPERIMENTAL RESULTS

Component		Theoretical @O/F = .080	Experimental Run Numbers 5AX- 75 O/F = .019	77 O/F = .110	76 O/F = .141
H_2	Hydrogen	51.2	28.7	34.2	34.0
N_2	Nitrogen	24.3	17.3	19.2	18.4
CH_4	Methane	19.6	42.9	39.4	37.2
CO	Carbon Monoxide	2.6	4.8	2.3	4.9
C_2H_6	Ethane	----	3.5	4.0	3.6
C_3H_8	Propane	----	0.8	0.5	0.5
NH_3	Ammonia	0.1	2.0	0.4	1.3
C_2H_4	Ethylene	< 0.1	< 0.1	< 0.1	< 0.1

Notes:

1) Experimental analyses made by mass spectrometer with specie presence confirmed by infrared and gas chromatographic techniques.

2) Theoretical analysis predicts presence of solid carbon - not collected in experimental samples.

TABLE V

RECOIL-COMPENSATING ROCKET DESIGN DATA

Thrust, lb	100
Chamber pressure, psia	300
Nozzle throat area, sq. in.	0.248
Nozzle throat diameter, in.	0.562
Nozzle exit diameter, in.	1.05
Chamber characteristic length, L*, in.	34
Chamber diameter, in.	1.75
Chamber length, in.	3.2

PROPELLANT SYSTEM DESIGN DATA

	Oxidizer	Fuel
Propellants	N_2O_4	UDMH
Flowrate, lb/sec	0.268	0.178
Flowrate, cu. in./sec	5.14	6.34
Propellant specific gravity	1.44	0.78
Injector pressure drop, psi	100	100
Propellant line pressure drop, psi/ft	3-4	3-4
Velocity in propellant lines, ft/sec	17	21

flow rate and mixture ratio control. Venturis can be sized to provide the desired flow rates for propellant tank pressures at any convenient level higher than a minimum determined by chamber pressure. The flow rate is a function of upstream pressure and density only and is not affected by events or fluctuations downstream of the venturi, provided that the downstream or back pressure does not exceed about 85% of the upstream pressure.

The rocket employs a vortex injection system which has proven very successful at RMD for many propellant combinations. With this injection system, the fuel is injected tangentially at the periphery of the chamber and the oxidizer is injected radially from the center of the chamber. Advantages of vortex injection include low heat losses to the chamber walls, minimizing cooling requirements, simple and inexpensive fabrication and relatively small combustion chamber volume for good performance.

Figure 3 shows a plumbing schematic of the entire system. By proper valve operation, the CRR alone, the gas generator alone or both could be operated in order to investigate either individual or combined characteristics.

2.4.2. System Response and Transient Studies

There is no doubt that a rocket can be used to provide forward thrust for balancing the reaction of a rearward thrust during steady-state operating conditions of a flamethrower. The ability to match transient thrust effects using the components provided with the government-furnished Flamethrower Research Device remained to be demonstrated, however. For the forces in either direction due to gel flow and recoil rocket operation, transient times are directly related to the particular valve designs, although other factors also have an effect. Figure 9 depicts a dimensionless thrust trace with the various parameters that affect starting and shutdown transients of the rocket. It can be seen that thrust transients of a liquid propellant engine generally depend on,

a. Propellant valve operating times.
b. Injector manifold volume.
c. Ignition time delay for the propellants.
d. Characteristic length (c*) as determined by chamber volume.

Items a and b affect the starting thrust transient by influencing the rate at which quantities of propellants are introduced into the combustion chamber before steady-state flows are attained. The duration of the starting thrust transient, therefore, is a direct function of the time necessary to fully open the propellant valves, completely fill the injector manifolds and attain steady-state flow rates. Although it is possible to provide variable flow rates during the starting transient by using valves specifically designed for this purpose, this added complexity is probably not warranted, particularly in the breadboard feasibility model.

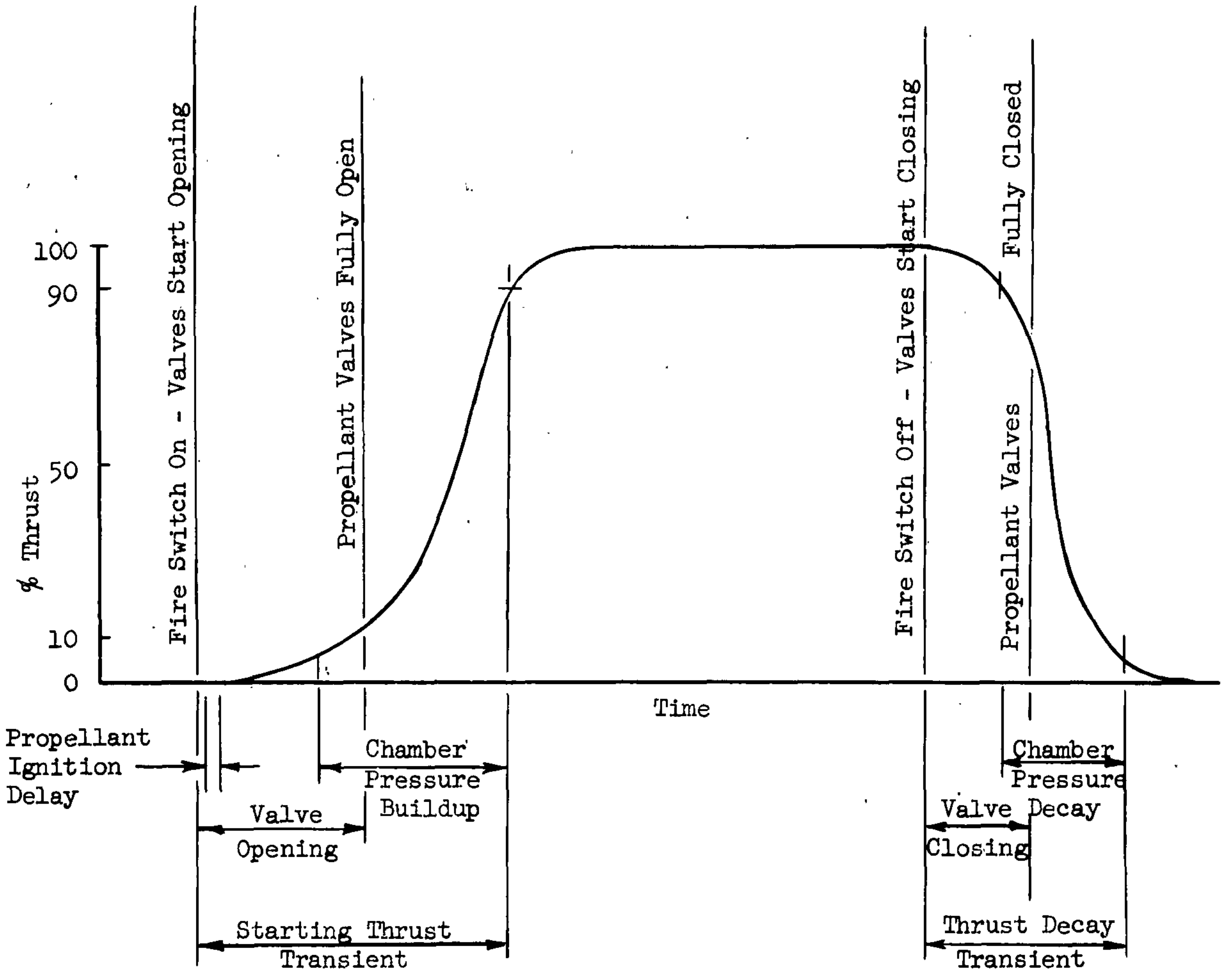


Figure 9. Bipropellant Rocket Thrust Chamber Response Terminology

The ignition time delay of hypergolic propellants is the period from initial mixing of the two propellants to the time when a noticeable reaction can be detected. For the propellant combination being used (N_2O_4/UDMH), ignition time delay is negligible with respect to other delays.

The characteristic length (L*) of a rocket engine is defined as the ratio of combustion chamber volume to throat area and can determine to a large extent the shape of the chamber pressure-time curve. In general, the chamber volume is chosen as the minimum size which permits attainment of a high per cent of theoretically available performance for a given propellant combination. It can be shown that for relatively fast acting propellant valves, increasing the chamber volume by a factor of two increases the thrust transient duration by the same factor provided the thrust level is the same in both cases. Since performance is not nearly as dependent on chamber size as the transient duration can be, chamber volume is a possible means of transient duration adjustment particularly if a longer transient is desired, although the thrust decay at shutdown will be similarly effected by such adjustments.

Of the methods available for transient control, control of the propellant flow has the greatest potential for producing desired thrust variations. The extent to which propellant flow in a simple system can be varied, however, is limited by practical considerations.

A 2-in. ball valve was used as the gelled gasoline expulsion valve. This design was selected since it provided a straight-through flow path, minimizing interference with the gel rod. This valve, which was an integral part of the government-furnished Flamethrower Research Device, was manufactured by Jamesbury Valve Corporation. The valve has an electric solenoid which controls the application of 120 psi control gas to a pneumatic cylinder which opens and closes the valve. This type of device is inherently slow acting compared with the direct-acting solenoid valves used for the recoil rocket and resulted in measured thrust transients of 100-220 milliseconds for gel flow initiation and 55-110 ms for stopping gel flow. Since valve design or major gel valve revision was not within the scope of this contract, it was felt that the ability to match recoil and counter-recoil forces with the present hardware could best be obtained by varying the CRR characteristics. In the development of an operational weapon, however, the characteristics of both the fuel gel valve and the recoil rocket can be mutually adjusted.

The data tabulated in Table VI represent the results of tests to measure and define transient durations (Test Series 1 and 2) and modifications to match transient characteristics to the fixed characteristic of the gel release valve (Test Series 3). In all tests, no changes were made to the rocket nozzle, combustion chamber, or injector. Injector volumes were effectively changed by varying the feed line length between the injectors and propellant valves. The three basic series of tests shown represent three

TABLE VI

COUNTER-RECOIL ROCKET TRANSIENT SUMMARY

Test No.	P_{Ch} Start	P_{Ch} Decay	Thrust Start	Thrust Decay	Comments
	(All values in milliseconds)				
4914	160	280	80	100	Used pneumatically operated Annin valves plumbed to provide minimum injector volume. Transient curves show smooth rise with no overshoot, smooth decay. Used RMD test stand, parallelogram mount.
4915	180	280	80	80	
4916	200	250	100	100	
4917	200	230	100	100	
4918	200	240	80	150	
5203	50	20	15	85/40	Used electric solenoid valves - Marotta MV100 WD plumbed to provide minimum injector volume. Double tabulation reflects recorded overshoot and smooth transient values.
5204	50/15	25	15	90/45	
5205	35/20	20	15	---	
0001	70	30	45	50	Used electric solenoid valves - Marotta MV100 WD plumbing varied to provide variable injector volumes. Runs 0001, 2 made with simultaneous, start, minimum injector volume while 0004 through 15 were made with varying volumes, time delays between valve actuation and de-energization.
0002	45	25	35	40	
0004	130	110	30	50	
0005	120	80	25	40	
0006	40	80	35	65	
0007	110	50	30	30	
0008	130	60	35	40	
0010	155	130	45	35	
0011	155	65	30	40	
0012	100	100	30	35	
0013	150	50+	35	35	
0014	60	70+	30	40	
0015	155	60+	30	35	

sets of propellant valves having different transient characteristics. The first set of valves was relatively large, slow-acting, and produced smooth chamber pressure and thrust curves of long transient duration. The second series of tests was made with fast responding solenoid valves and minimum injector volumes. The third series also was made with fast response valves, but valve timing and injector volume changes were made to determine effects on the rocket transients.

Chamber pressure transient durations were varied from 45 to 155 milliseconds by these changes, but the shape of the chamber pressure/time curve was not altered significantly. That is, it was possible to control the time at which chamber pressure started to rise, but the subsequent rate of rise was not appreciably affected. Should it be necessary to control the rate of rise in an operational unit, propellant valves which throttle during the opening period, perhaps with a pintle or slow-moving poppet, could be used. Similarly, combustion chamber size variations can be used to affect the rate of rise.

Although the rocket stopping transient in general is similar in duration to the starting transient, the cessation of gel thrust can vary drastically under some conditions. In those cases in which all gel was expended before the gel valve was closed, the gel thrust decayed in about 15 milliseconds. Since the counter-recoil rocket can be designed conveniently for only one stopping transient duration, it is probably desirable to provide automatic termination of operation in an operational unit before the gel is completely expelled. Thus, all shutdowns would be similar and both start and stop transients could be matched.

2.5 Gel Expulsion Tests

With the establishment of the Flamethrower Firing Range and the completion of successful Flamethrower Research Device water expulsion tests, ignited gel firings were made. The facilities available at the range are described in Section 6 and a photograph of the experimental liquid propellant system is shown in Figure 10.

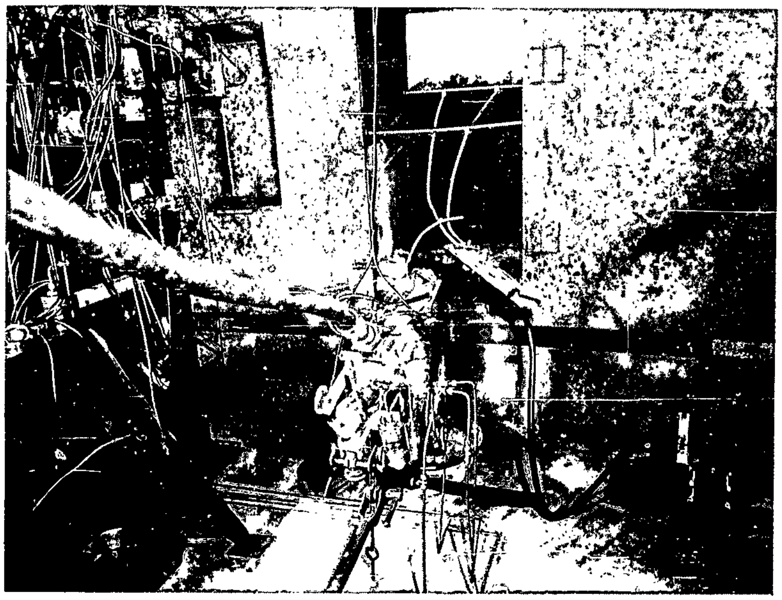
Gel system configuration is extremely important in obtaining maximum range. The gel flow passages determine to a large extent the type of gel rod that is formed during expulsion from the flamethrower gun. The factors which apparently affect gel rod integrity influenced to some degree the direction of the test program and are discussed in detail in Section 4.

Table VII lists representative data taken during the liquid propellant-actuated flamethrower gelled gasoline expulsion tests. The values noted in the table represent typical values that were measured during the test. Since some of the tests extended over long periods of time and included many bursts, it is not practical to include all data points. However, the points shown are typical for the particular test.

Propellant tanks
behind panel

Ten foot
length
flexible
hose

Gel Tank



Supporting
structure for
ignition system

Motor with
flexible drive
shaft

Tripod mount
with turn-
buckle/floor
attachment

Propellant and
purge lines
leading to counter
recoil rocket

Figure 10. Flamethrower Range Experimental Liquid Propellant Flamethrower Research Device

TABLE VII

LIQUID PROPELLANT FLAMETHROWER GELLED GASOLINE EXPULSION SUMMARY

Test No. FTXL	No. of Bursts	GG P_{Ch} (psig)	Gel Nozzle Inlet (psig)	Max. Accum. Temp. (°F)	Thrust (lbs)	Gel Igni-tion	Range (yds)	Average Gel Flow Rate (gal/sec)	Comments (Based partly on high speed film results)
1	2	395*	335*	--*	+113*	Yes	10-90	2.01	Test of chromyl nitrate ignition system.
2	2	430	352	--	+108	Yes/No	18-88/-	2.06	Differences in gel rods from burst to burst.
3	1	---	---	--	----	Yes	----	----	See Runs 5, 6.
4	2	506 472	426 393	600 600	+131 +156	Yes Yes	50-100 100-120	2.36	Distinctly different gel rod appearance in bursts 1 and 2.
5	-	---	---	---	----	No	----	----	Low electrical power supply setting affected normal gas generator operation.
6	-	---	---	---	----	No	----	----	
7	1	---	---	---	----	No	----	----	Gel rod appearance improved as gel nozzle inlet pressure decreased.
8	3	450	379	300	----	No	30-68	----	Expelled gel contained many air bubbles.
9	2	474	407	460	----	No/Yes	40-60/ 30-90	2.30	Apparent entrapped air affected gel rod continuity.
10	4	450	379	360	----	No	30-60	2.17	Apparent spiral effect in gel rod.
11	2	---	---	400	----	Yes	70-120	2.36	Poor homogeneity of gel rod—air bleed installed, piston O-rings replaced.

*Typical Value During Test
+Thrust Due to Gel, -Thrust Due to Recoil Rocket

TABLE VII (Cont'd)

LIQUID PROPELLANT FLAMETHROWER GELLED GASOLINE EXPULSION SUMMARY

Test No. FTXL	No. of Bursts	GG P_{Ch} (psig)	Inlet (psig)	Max. Accum. Temp. (°F)	Thrust (lbs)	Gel Igni-tion?	Range (yds)	Average Gel Flow Rate (gal/sec)	Comments (Based partly on high speed film results)
12	3	443	348	450	+121	No	35-65	----	Gel transient studies.
13	2	375	278	390	+ 98 -105	No	40-62	2.06	Simultaneous gel expulsion, recoil rocket operation.
14	3	439	343	---	0	No	40-60	2.06	Transient matching test with time delay relays.
15	8	418	308	440	+ 15	No	35-68	2.01	
16	3	396	298	---	+ 92 - 98	No	35-55	1.95	

+Thrust Due to Gel, -Thrust Due to Recoil Rocket

Since ignition of the gel rod does not affect operation of the GG or expulsion system, most tests were made without ignition because of the limited supply of chromyl nitrate and so that rod characteristics would not be obscured by combustion. Since the range attained is significantly longer with ignition, however, the actual range attained in the unignited tests is not a true indication of the flamethrower capabilities. In general, however, the ignited range is approximately twice the range achieved with unignited gel.

Thrust measurements were obtained with the Flamethrower Research Device using two load cells as described in Section 5. Figure 11 shows the relation between nozzle inlet pressure and thrust for the ½-inch diameter nozzle. The data for the second burst during FTXL 4 is shown separately since some characteristic of this 1.7 second burst caused it to differ markedly from other shots. When compared to the first burst, the second produced greater thrust and longer range although system pressures were comparable. This shot resulted in a maximum range of 120 yards, the longest achieved with the liquid propellant flamethrower system in ignited firings. Subsequent attempts to duplicate this shot were not successful. Some of the reasons for the inconsistent range obtained are discussed in Section 4.

Runs FTXL 8-11 were made in order to observe gel rod characteristics, investigate the effects of storage on gels and observe general system operation.

Runs FTXL 12-16 representing 19 separate bursts were studies of 1) the transient effects of gel bursts, controlled by a ball valve, and 2) the transient thrust phenomena in matching the CRR operation with gel valve opening. Thrust rise due to gel expulsion had an average transient duration of 75 milliseconds while the CRR had an average transient duration of 40 milliseconds. Time delay circuits were incorporated in the recoil rocket control circuits so that both the starting and shutdown transients could be adjusted in order to match the flamethrower recoil transients. Starting transient unbalance was held to less than several pounds in one case and less than 30 milliseconds duration in another. Thus, it is considered that adequate compensation for F / T thrust with a rocket system is feasible.

Although thrust matching was achieved with the present hardware through the use of time delay relays to sequence the occurrence of particular events, in an operational design it is felt that the necessary timing can be made an inherent feature of the system. The time delay approach was necessary with the breadboard hardware because of the wide range of characteristics between the fuel gel valve and the recoil rocket valves which were available.

Figure 12 shows the oscillograph record from Run FTXL 16. The four traces shown are (1) fuel tank gas pressure (gas-side of the positive expulsion piston in the tank), (2) thrust, (3) gel nozzle inlet pressure, and (4) counter-recoil rocket chamber pressure. The gas generator was

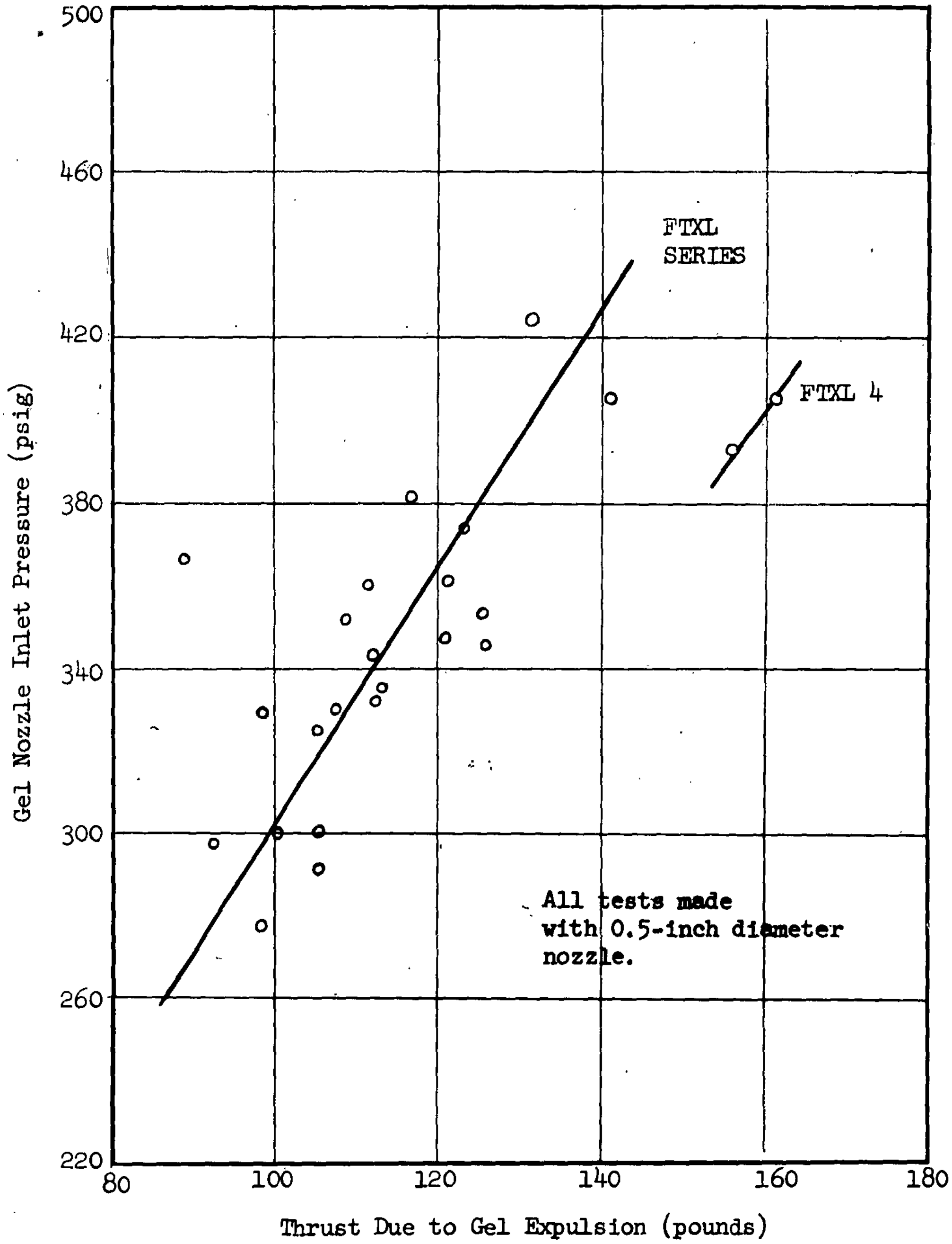


Figure 11. Variation of Thrust Due to Gel Expulsion with Gel Nozzle Inlet Pressure

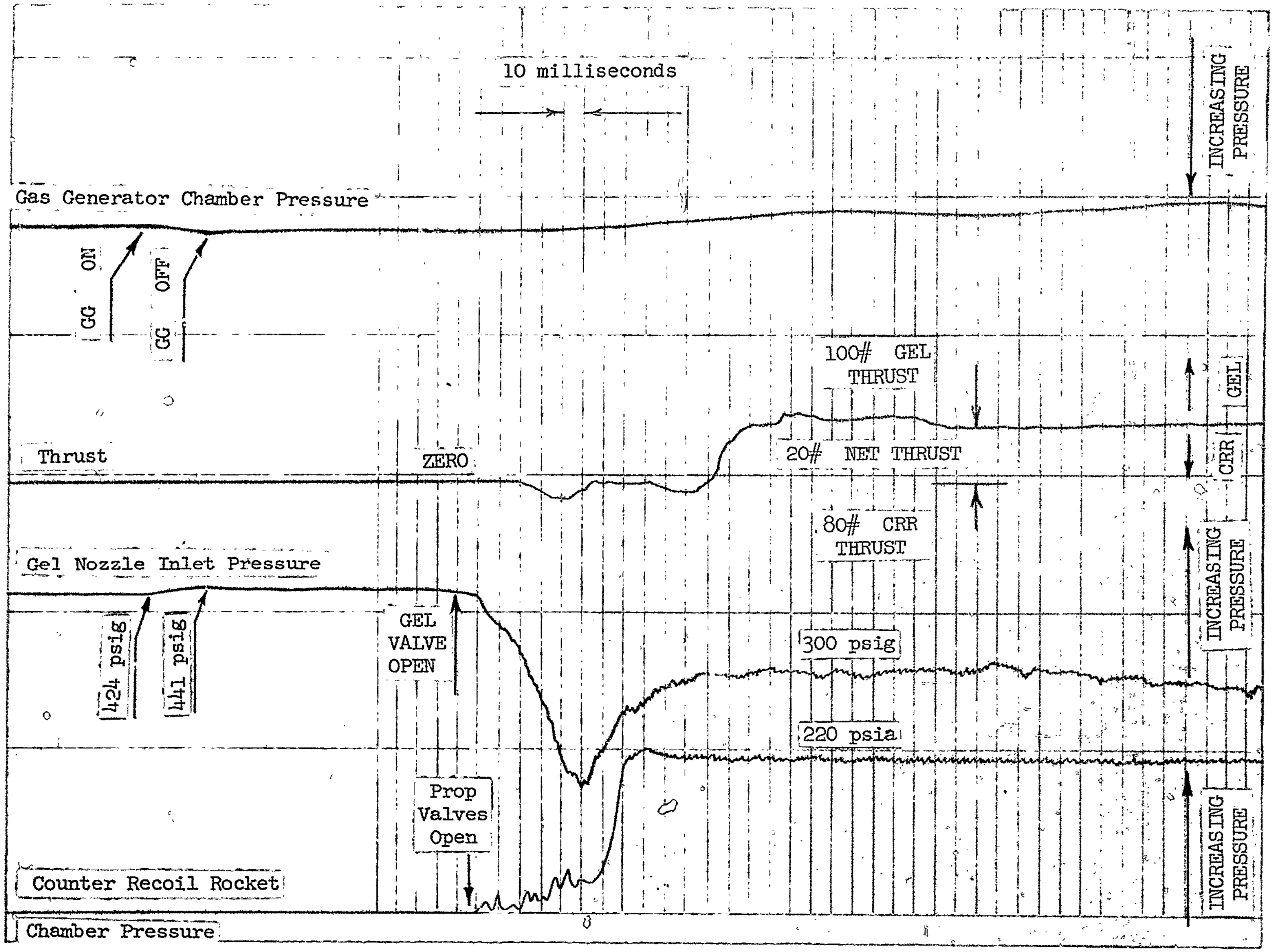


Figure 12. Recorded Trace of Simultaneous Gel Expulsion and Counter Recoil Operation for the Liquid Propellant-Actuated Flamethrower

started prior to the time shown in the figure. The gas generator is being controlled by a pressure switch, thus maintaining fuel tank gas pressure and gel pressure at about 450 psig. When the FIRE switch was thrown, the gel valve was energized to open. As it started to open, the pressure at the nozzle inlet decayed until gel flow was initiated. Gel pressure then rose for approximately 100 milliseconds after FIRE until steady-state gel flow had been reached.

Simultaneously with energization of the gel valve, the time delay relay controlling the recoil rocket was energized. After a preset 20 millisecond delay period, the rocket propellant valves were energized, permitting propellant flow and chamber pressure rose as indicated. In this particular case, the CRR transient period was 70 milliseconds after the initial chamber reaction or 90 milliseconds after FIRE. The CRR thrust curve would have essentially the same shape as the chamber pressure curve if fired alone.

The transient thrust match is evident from the trace. Recoil rocket thrust was about 20 lbs less than the recoil due to expulsion of the gel from the flamethrower nozzle in this case. This minor variation, however, is easily remedied by increasing rocket propellant flow rates slightly either by increasing propellant tank pressures or by adjusting the flow control venturis.

Shutdown transients can be controlled in the same manner. On shutdown the slower-acting gel valve was de-energized first, permitting it time to begin closing first. The faster acting CRR propellant valves were then de-energized after a preset time delay. This thrust matching procedure, while suitable for the breadboard unit, would not be required for a field unit. Thrust matching in a prototype unit would be inherent in the valve design.

The one possible exception in matching shutdown transients occurs when all the gel has been expelled before the burst is terminated. Here, the gel thrust ceases in approximately 15-20 milliseconds since it does not depend on gel valve closing time. To avoid the occurrence of different transient durations of this nature it will be desirable in prototype units to sense exhaustion of the gel and terminate operation before this occurs. Thus, all shutdowns will be similar and one method of shutdown operation will be suitable for all cases.

As indicated in Table VII, there is a significant pressure drop between the gas generator and the gel nozzle. The pressure drop is also inconsistent from run to run even under identical operating conditions. For example, no physical changes were made in the flamethrower or the gas generator in Runs FTXL 4, 7-11. The gasoline gel was taken from several batches which had been made approximately one month and 3½ months prior to use. Pressure measurements and observations of the gel rod

showed distinct differences. Consistent correlation between gel tank pressure and thrust could not be obtained indicating that gel characteristics varied from test to test and batch to batch although external conditions affecting the gel were kept as nearly similar as possible. Complete healing of the gel in the system was assured by waiting a minimum of 45 minutes and a few times as long as several days before expelling the gel. It would be expected, therefore, that gel flow characteristics should repeat reproducibly. They did not. The observations of gel characteristics are discussed further in Section 4.

TABLE II

LIQUID PROPELLANT GAS GENERATOR TEST SUMMARY

Run No. 5AX	W_o (lb/sec)	W_f (lb/sec)	W_t (lb/sec)	O/F	P_{ch} (psia)	T_{ch} (°F)	c* (fps)	$P_{Accum.}$ (psia)	$T_{Accum.}$ (°F)	Hardware Changes Before Run	Purpose
5119										GG Chamber used with	System Check
5120										sonic orifice	
5121	.0107	.182	.193	.059	500	350	1650	Not Applicable		Moved surge limiting	Correct Ox fl
5122	.0146	.177	.192	.082	525	350	1780			venturi to minimize	ing syste
5123	.0155	.167	.183	.093	540	355	1940			peaks	
5124		.131			425	330					
5125		.181			460	345					
5126	.0138	.173	.187	.080	530	360	2120			Moved T.C. junction to	Determine eff
5127	.0138	.164	.178	.084	550	375	2310			1/4" from ID chamber	chamber locat
5128	.0142	.158	.172	.090	580	380	2520			wall.T.C. 1" from noz-	temperature i
5129	.0152	.1275	.143	.120	620	590	3240			zle (axially)	
5130	.0141	.176	.190	.080	521	390	2050			Reduced volume of in-	Reduce transi
5131	.0144	.160	.174	.090	572	530	2450			let lines,reversed	more reliable
5132	.0156	.136	.152	.115	589	620	2900			chamber so that TC 1"	measurements
5133	.0169	.127	.144	.133	604	570	3130			from injector, 22°from	
5134	.0187	.122	.141	.152	619	590	3270			top, 3/16" exposed.	
5135	.0167	.174	.191	.096	572	450	2640			Opened Nozzle up to	Reduce P_{ch} to
5136	.0178	.167	.185	.106	604	600	2880			3/16" Dia.	range with pr
5137	.0187	.160	.179	.117	627	610	3090			A_t = .0274	rate
5138		.153	.173		647	590	3300				
5139	.019	.176	.2		543	410	3100			Opened noz. to #3 drill	Reduce P_{ch} to
5140	.0186	.176	.195	.106	516	410	3030			(.213) A_t = .0356	range with pr
5141	.0193	.176	.195	.110	531	470	3120				rate
5142	.0189	.177	.196	.107	519	430	3040			Put tube on outlet of GG	Find out if I
5143	.0189	.178	.197	.106	516	430	3000			to trap particles in	solid particl
										exhaust	exhaust
5155	.0178	.171	.199	.104	550	1000	3160	65	600	Put accumulator on GG outlet, #3 orifice between GG & Acc, put prop valves on engine--elim. blowdowns	Simulate flam conditions,ch of system cha
5156	.0171	.175	.192	.098	572	910	3410	434	590	Put #3 orifice on Acc.	
5157	.0187	.173	.192	.108	587	790	3500	452	660	outlet	
5158	.0165	.178	.195	.093	575	800	3380	575	870	Removed orifice between	Det. necessit
5159	.0193	.176	.195	.110	578	1000	3440	575	1160	GG & Acc.	term. orifice
5160	.0138	.178	.192	.0775	589	880	3510	589	1190		performance v
5161	.0145	.177	.193	.082	584	850	3460	585	1210		with O/F chan

TABLE II

LIQUID PROPELLANT GAS GENERATOR TEST SUMMARY

c* (fps)	$P_{Accum.}$ (psia)	$T_{Accum.}$ (°F)	Hardware Changes Before Run	Purpose	Remarks/Conclusions
			GG Chamber used with sonic orifice	System Check out	
1650 1780 1940	Not Applicable		Moved surge limiting venturi to minimize peaks	Correct Ox flow recording system	Surges inherent with this DP cell and method of mounting--best location for surge limiter probably on inlet to DP cell.
2120 2310 2520 3240			Moved T.C. junction to 1/4" from ID chamber wall. T.C. 1" from nozzle (axially)	Determine effect of chamber location on temperature indication	T_{ch} values are at steady state. Higher values at shutdown. Liq. must be spraying T.C. Noted gummy residue in engine.
2050 2450 2900 3130 3270			Reduced volume of inlet lines, reversed chamber so that TC 1" from injector, 22° from top, 3/16" exposed.	Reduce transients, give more reliable temp. measurements.	Available locations for measuring T_{ch} not satisfactory. Black gummy residue in eng.
2640 2880 3090 3300			Opened Nozzle up to 3/16" Dia. A_t = .0274	Reduce P_{ch} to desired range with proper flow rate	Chamber pressure still too high
3100 3030 3120			Opened noz. to #3 drill (.213) A_t = .0356	Reduce P_{ch} to desired range with proper flow rate	Further changes not warranted in this phase of program
3040 3000			Put tube on outlet of GG to trap particles in exhaust	Find out if liquid or solid particles in exhaust	Nothing collected in 5 & 20 sec. tests
3160	65	600	Put accumulator on GG outlet, #3 orifice between GG & Acc, put prop valves on engine--elim. blowdowns	Simulate flamethrower conditions, check-out of system changes	Orifice on Acc. outlet req'd to simulate moving piston
3410 3500	434 452	590 660	Put #3 orifice on Acc. outlet		
3380 3440 3510 3460	575 575 589 585	870 1160 1190 1210	Removed orifice between GG & Acc.	Det. necessity for interm. orifice, establish performance variations with O/F changes	See approp. graphs for O/F vs. $Temp._{ch}$

TABLE II (Continued)

LIQUID PROPELLANT GAS GENERATOR TEST SUM

Run No. 5AX	Wo (lb/sec)	Wf (lb/sec)	Wt (lb/sec)	O/F	P_{ch} (psia)	T_{ch} °F	c*	$P_{Accum.}$ (psia)	$T_{Accum.}$ (°F)	Hardware Changes Before Run	Pu
5162	.0113	.178	.189	.0635	584	740	3540	584	1210		
5163	.0083	.1782	.187	.0465	568	370	3480	569	1030		
5164	.0063	.1782	.184	.035	550	300	3420	549	790		
5165	.0075	.1782	.186	.042	580	300	3570	564	910		
5166	.0126	.186	.199	.068	522	650	3760	500	1185	New P_{ch} teledyne--nitrogen line plumbed into Accum.	St
5167	.0120	.186	.198	.065	522	750	3780	500	1200		
5168	.0106	.186	.197	.057	572	700	---	553	310	N_2 back pressure = 446/428 psia	Se ag
5169	.0070	.186	.193	.042	618	270	---	594	220	N_2 back pressure = 512/494 psia	pr
5170	varies	.189	--	var.	519	660		498	970	Installed Pr. Switch to control GG, setting–486/282 psig, .238 orifice on Accum. outlet.	Ch op
5171	varies	-- Pulses too short to get flow measurements	--		541	500		520	830	.1695 orifice on Accum. outlet	Co en
5172	varies	--	--		553	380		534	720	.120 orifice	
5173	varies	--	--		570	390		553	750	Inst. Pr. Sw. #2 500/440 psig	Na
5174	.0152	.189	.204	.08	475	1230	3340		1060	Disconnect Pr. Sw.--put .238 orifice on Acc. outlet	De re
5175	.0148	.188	.203	.079	479	1210	3380	474	1010		Tal
5176	.0233	.165	.188	.141	448	1105	3380	444	1060		co
5177	.0197	.179	.199	.110	462	1090	3330	465	1040		ti
5178	.0182	.138	.206	.097	415	620	--	296	--	Moved thermocouples,	Ex
5179	.0184	.188	.206	.098	428	800	--	311	405	cleaned chamber--put	du
5180	.0178	.188	.206	.095	430	1000	3000	314	550	.238 orifice between	go
5181	.0173	.188	.205	.092	420	1110	2930	318	570	GG & Accum.	co
5182	.0233	.179	.202	.13	481	800	--	368	830		

TABLE II (Continued)

LIQUID PROPELLANT GAS GENERATOR TEST SUMMARY

ch (°F)	c*	$P_{Accum.}$ (psia)	$T_{Accum.}$ (°F)	Hardware Changes Before Run	Purpose	Remarks/Conclusions
-0	3540	584	1210			
70	3480	569	1030			
00	3420	549	790			
00	3570	564	910			
50	3760	500	1185	New P_{ch} teledyne--nitrogen line plumbed into Accum.	Standard for comparison	No problems starting with pressure in chamber
50	3780	500	1200			
00	---	553	310	N_2 back pressure = 446/428 psia	See if engine starts against back pressure present problems	
70	---	594	220	N_2 back pressure = 512/494 psia		
50		498	970	Installed Pr. Switch to control GG, setting— 486/282 psig, .238 orifice on Accum. outlet.	Check out automatic operation	
00		520	830	.1695 orifice on Accum. outlet	Corresponds to different piston speed	
30		534	720	.120 orifice		
90		553	750	Inst. Pr. Sw. #2 500/440 psig	Narrower dead band	Measured chamber temps too low to be realistic prob. because of 2-phase flow--Accum. temps reasonable--pulsing reduces meas. temp. to about 80% of true gas temp--see run 70 T_{Acc}.
30	3340		1060	Disconnect Pr. Sw.--put .238 orifice on Acc. outlet	Determine extent of residue formation	Comb. products coat entire inside of accumulator-water soluble, can be cleaned off.
.0	3380	474	1010		Take gas samples to compare with theoretical	See separate discussion
05	3380	444	1060			
90	3330	465	1040			
20	--	296	--	Moved thermocouples, cleaned chamber--put .238 orifice between GG & Accum.	Examine combustion products--attempt to find good T.C. location for consistent temp. meas.	Inside of Accum. heavily coated after these 5 runs--temp. traces erratic during runs probably due to excessive deposits
00	--	311	405			
00	3000	314	550			
.0	2930	318	570			
00	--	368	830			

TABLE II (Continued)

LIQUID PROPELLANT GAS GENERATOR TEST SUMMARY

Run No. 5AX	W_o (lb/sec)	W_f (lb/sec)	W_t (lb/sec)	O/F	P_{ch} (psia)	T_{ch} (°F)	c*	$P_{Accum.}$ (psia)	$T_{Accum.}$ (°F)	Hardware Changes Before Run	Purpos
5183	.022	.178	.200	.123	477	860	3410	374	780		
5184	.022	.179	.201	.123	500	2250	--	400	930	Installed centrif. separator on side port of Accum.	Try tc separa
5185	--	--	--	--	--	--	--	--	--	Installed second T.C. in Accum.--still using separator	Ditto
5186	.0133	.182	.171	.073	546	1470	4000	546	1160	Injector #2 installed	Detern inject inate
5187	.009	.162	.171	.055	683	1220	--	690	1190	Put filter on separator outlet	
5188	--	.173	--	--	688	1070	--	692	1220		
5189	.014	.138	.152	.10	671	1470	--	672	1240		
5190	.0199	.188	.208	.106	441	2060	3080	448	1260	GG & Accum. -- .213	Obtair for Ir
5191	.0182	.187	.205	.097	460	1880	3210	460	1270		
5192	.0159	.188	.204	.085	460	1830	3230	460	1310		
5193	.0144	.187	.201	.077	468	1500	3340	469	--		
5194	.0132	.188	.201	.070	460	1360	3280	459	--		
5195	.0141	.188	.202	.075	449	1370	--	--	870	Put separator directly on GG outlet--no accum.	Examir
5196	.0135	.187	.201	.072	416	1220	--	--	820		

TABLE II (Continued)

LIQUID PROPELLANT GAS GENERATOR TEST SUMMARY

c*	$P_{Accum.}$ (psia)	$T_{Accum.}$ (°F)	Hardware Changes Before Run	Purpose	Remarks/Conclusions
3410	374	780			
--	400	930	Installed centrif. separator on side port of Accum.	Try to find some way of separating comb. prod.	Nothing collected in separator
--	--	--	Installed second T.C. in Accum.--still using separator	Ditto from Run 78	Ran out of fuel
4000	546	1160	Injector #2 installed	Determine whether 2nd injector design will eliminate residue	Chamber temp. meas. at lower O/F Unsat. Two Accum. TC do not agree perfectly.
--	690	1190	Put filter on separator outlet		Powdered carbon collected in separator--no liq. or gum.
--	692	1220			Liq. collected in accumulat.
--	672	1240			
3080	448	1260	GG & Accum. -- .213	Obtain O/F vs T_{ch} data for Inj. #2	See approp. graph
3210	460	1270			
3230	460	1310			
3340	469	--			
3280	459	--			
--	--	870	Put separator directly on GG outlet--no accum.	Examine comb. Products	No comb. products collected
--	--	820			

TABLE III

LIQUID PROPELLANT GAS GENERATOR AND SYSTEM PRESSURIZATION SU

	GG					Gas Side of Piston	Liq. Side Pist.	Retro Rocket				
Run No. 5AX	w_o/w_f (lb/sec)	w_t (lb/sec)	O/F	P_{ch} (psia)	T_{ch} (°F)	P_{tank}/T_{tank} (psia/°F)	P_{gel} (psig)	w_t (lb/sec)	O/F	P_{ch} (psia)	Thrust (lbs)	Hardwa ges B Ru
5197	--	--	--	--	380							Inst. tank] contr
5198	--	--	--	453	1750max	453/250	--					
5199	--	--	--	485	1690max 1100avg	465/450	--					
5200				500	1550max	535/580	520					
5201	var/.208	--	Variable	440	1400max	470/640	450				140±7	Attac load ro's in-ne ies i
5202							--	--	--	277	-75	Retro only
5203							--	.419	1.45	252	-93	
5204							--	.415	1.37	261	-97	
5205	var/.191	--	Variable	--	1270max	460/640	470	.421	1.36	255	-98	Simul & GG
5206	var/.202	--	Variable	--	1610max	--	440	.405	1.40	250	--	
5207	var/.202	--	Variable	--	1740max	469/660	460	.418	1.33	250	-92	
5208	.018/.151	.169	.119	--	1390max	---/550	440				+132	Inst. turi --dis retro
5209	.015/.152	.167	.101	440	1700max	430/600	400				+145 +130	
5210	.025/.149	.174	.168	385	1530max	376/550	370					
5211	.025/.149	.174	.168	428	1450max	418/500	400					

TABLE III

QUID PROPELLANT GAS GENERATOR AND SYSTEM PRESSURIZATION SUMMARY

	Gas Side of Piston	Liq. Side Pist.	Retro Rocket						
Tch (°F)	Ptank/Ttank (psia/°F)	Pgel (psig)	Wt (lb/sec)	O/F	Pch (psia)	Thrust (lbs)	Hardware Changes Before Run	Purpose	Remarks/Conclusions
380 .750max	453/250	--					Inst. GG on gel tank pr. sw. controlling	System checkout	Fixed GG flow rate may not be able to match requirements at all times
.690max .100avg	465/450	--						Water expulsion	No system or hardware problems evident
.550max	535/580	520						Water exp.--det. temp.-time char.	
.400max	470/640	450				140±7	Attached Army load cell-retro's plumbed in-new venturies installed	Prepare to run GG and retros from same tankage	
		--	--	--	277	-75	Retro firing only	Check out retro system	Instrumentation difficulties
		--	.419	1.45	252	-93			
		--	.415	1.37	261	-97			
270max	460/640	470	.421	1.36	255	-98	Simult. retro & GG	Demonstrate design operation. Operate in bursts, same tankage for GG & retro	No problems evident
610max	--	440	.405	1.40	250	--			
740max	469/660	460	.418	1.33	250	-92			
390max	---/550	440				+132	Inst. #80 venturi in ox GG --disconnected retro	Bursts: Determine O/F vs. Temp/relations	See graph for O/F vs. T GG flow rate of .174
700max	430/600	400				+145 +130		Single Shot: Det. oper. at lower flow rates	
530max	376/550	370						Single Shot	
450max	418/500	400						Bursts	

TABLE III (Continued)

LIQUID PROPELLANT GAS GENERATOR AND SYSTEM PRESSURIZATIO

Run No. 5AX	GG					Gas Side of Piston	Liq. Side of Piston	Post-Run Residue		
	W_o/W_f (lb/sec)	W_t (lb/sec)	O/F	P_{ch} (psia)	T_{ch} (°F)	T_{tank} (F)	P_{gel} (psig)	(Liquid) (lb)	GG C* (fps)	Hardwa ges Be Ru
5226	.016	.176	.099	260	--				2120	Gas ge
5227	.015	.198	.083	284	2180				2060	run wi
5228	.016	.163	.109	279	1910				2450	orific
5229	.021	.165	.146	297	1940				2580	
5230	No Test									
5231	.024	.182	.15	493	--	450	460	.53		Assemb plete used M fuel
5232	.024	.182	.15	500	--	700	450	1.15		
5233	.035	.174	.25	446	890max	660	470	.53		Instal new ve
5234	No Test									
5235	.030	.168	.22	504	1930	550	520	.50		10 psi pressu instal

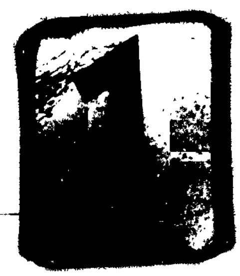


TABLE III (Continued)

QUID PROPELLANT GAS GENERATOR AND SYSTEM PRESSURIZATION SUMMARY

	Gas Side of Piston	Liq. Side of Piston	Post-Run Residue				
T_{ch}	T_{tank}	P_{gel}	(Liquid)	GG C*	Hardware Changes Before Run	Purpose	Remarks/Conclusions
(°F)	(F)	(psig)	(lb)	(fps)			
-- 2180 1910 1940				2120 2060 2450 2580	Gas generator run with .238 orifice	To evaluate MMH as fuel under steady-state conditions	Slight quantities of residues formed in chamber-water soluble. *c indicates that MMH will not give as good performance as UDMH
--	450	460	.53		Assembled complete system--used MMH for fuel	Determine magnitude of residue with MMH under cycling operations	Quantity and appearance of residue similar to UDMH
--	700	450	1.15			Compare single-shot expulsion with mult. bursts	4.0 sec to charge totally empty tank to 450 psig.
390max	660	470	.53		Installed new venturies	Above	GG seals leaked. Initial pressurization and hose flexing result in 80-lb ind. 160 ms req'd to reach 450 psi with full gel tank.
1930	550	520	.50		10 psi P pressure sw. installed	Evaluate tight tolerance pressure sw.	No significant difference, this flow rate matches requirements at end of run, too low in beginning

2

TABLE III (Continued)

LIQUID PROPELLANT GAS GENERATOR AND SYSTEM PRESSURIZA

	GG					Gas Side of Piston	Liq. Side of Piston	Retro Rocket			
Run No. 5AX	w_o/w_f (lb/sec)	w_t (lb/sec)	O/F	P_{ch} (psia)	T_{ch} (°F)	T_{tank} (F)	P_{gel} (psig)	O/F	P_{ch}	Residue (Liquid) (lbs)	Hardwa ges Be Ru
5236	.030 / .137	.167	.22	440	1800	690	440			.50	Instal pressu series throwe
5237											Change moved sw. to
5238	.025 / .113	.138	.22	450	1550	730	440			.32	chambe ter re UDMH
5239	.025 / .113	.138	.22	456	1500	480	480			.42	

TABLE III (Continued)

LIQUID PROPELLANT GAS GENERATOR AND SYSTEM PRESSURIZATION SUMMARY

	Gas Side of Piston	Liq. Side of Piston	Retro Rocket					
)	T_{tank} (F)	P_{gel} (psig)	O/F	P_{ch}	Residue (Liquid) (lbs)	Hardware Changes Before Run	Purpose	Remarks/Conclusions
0	690	440			.50	Installed 2nd pressure sw. in series with flame-thrower valve	To simulate "minimum energy" operation with mult. bursts	
						Changed venturies, moved GG pressure sw. to comb. chamber for better response. Used UDMH	Above	Safety did not open
0	730	440			.32		Above	This flow rate almost matched requirements
0	480	480			.42			

3.0 SOLID PROPELLANT-ACTUATED RECOIL-COMPENSATED FLAMETHROWER

In this section the original concept of an operational solid propellant-actuated, recoil-compensated, long range flamethrower is described. This is followed by a description of the workhorse model which was fabricated, and of the test firings in which this workhorse model was used. The excellent agreement of all major operating parameters with the predicted mode of operation will be noticed. A discussion of the characteristics of an operational prototype flamethrower follows next. Based upon preliminary investigation of costs of major components, it is anticipated that a combat model of this type flamethrower could be produced in large quantity for substantially less than $50 per unit.

3.1.1 Original Concept: Long Range Recoil-Compensated Flamethrower

Assume that the multi-shot capability requirement of the 10-gal flamethrower is waived in favor of a smaller, one-shot expendable unit (larger quantities of fuel can be delivered to a target by firing several individual shots). Pressurization of the gelled gasoline (gelgas) then can be achieved simultaneously with development of counter-recoil rocket (CRR) thrust simply by tapping combustion gas off the CRR motor chamber (mixing it with a coolant if necessary) and admitting this gas to the gelgas container or tank. Since only a single operation of the unit is required, it now is feasible to use a solid propellant both for the CRR and to pressurize the gelgas--in fact, a single propellant charge.

The solid propellant grain can be of a simple, economical slotted-tube configuration, cast in and casebonded to, thin-wall laminated paper tubes. The four slots at 90° can be cast into the grain in the customary manner, or may be sawed into the grain at the finishing operation when the grain is cut to length. This grain design develops very low stresses upon temperature cycling, and hence is very reliable; yet it has a burning area variation of less than 3% total. The finished grain will be bonded into the motor tube.

Because of the short burning time and the solids-free exhaust gas, an economical CRR nozzle probably can be produced from ordinary injection-molded fiber/phenolic compositions. This insert will be bonded into the aft end of the motor tube; shear stress on this bonded joint will be a mere 135 psi.

The solid rocket propellant contemplated (BF-122 Mod. 1) is a highly oxidized polysulfide/ammonium perchlorate (18/82 weight ratio) formulation with a flame temperature at 500 psia of ca. 4600° F. Obviously the portion of gas used to pressurize the gelgas tank will have to be cooled very substantially. Ammonium chloride, NH_4Cl, has been found to be a very effective solid for hot gas dilution and cooling. It is economical and stable at normal temperatures, but decomposes at ca. 660° F to yield NH_3

and HCl. Corrosivity of these gases is of no consequence in this short-duration, one-use application. Theoretical calculations show that temperatures below 700° F can be obtained with this system. The weight of NH_4Cl required is approximately 1.2 times the weight of propellant gas to be cooled (this is a small fraction of the total propellant weight) and a 100% excess is used to ensure adequate cooling. The NH_4Cl, in crystalline or pelleted form, will be inserted into the motor/gas generator body ahead of the propellant position, and will be confined between perforated paper/phenolic plates and metal screens. The propellant gas will flow through this coolant bed and directly into the gelgas container.

The gelgas will be sealed in a polyethylene (or other plastic) film bladder, and will be protected from direct impingement of hot gas by a polypropylene or other plastic cup-piston. This configuration provides both an excellent storage seal, isolation of pressurizing gas from gelgas (although this is not vital), and especially important, all-attitude positive expulsion capability. Initial pressurization of the gelgas will rupture the bladder at the gelgas nozzle and permit efflux of the fluid.

Ignition of the gelgas at the nozzle can be accomplished in several ways. One very simple, clean approach is shown in Figure 13. A laminated paper tube flash shield around the gelgas nozzle is lined with either a pyrotechnic mix, or perhaps preferably an aluminized composite propellant. The shield is closed at the front end by a plug which provides both weather and handling protection. A tight-fitting plastic plunger positioned in the gelgas nozzle contains a charge of small pyrotechnic (metal + oxidant) pellets, and the front end of the plunger carries a percussion primer or matchhead. When the expulsion of gelgas first begins as the result of initial pressurization, the gelgas bladder ruptures and the gelgas drives the plunger through the nozzle. The plunger tip strikes the end closure and initiates the matchhead, from which flame propagates in turn to the ignition booster composition and to the main flare propellant. It is anticipated that the time elapsed between initiation of the matchhead and ignition of the main propellant will be only a few milliseconds. The rise in pressure resulting from flare propellant combustion will eject the weather plug. If desirable, the plunger can be designed to crush longitudinally outside of the nozzle after impacting the front end until rising pressure blows off the weather plug. This postulated pressurized ejection of the weather plug provides several desirable features: The containment of pressure enhances reliability of ignition. The strong attachment of the weather plug required to resist pressurization to several hundred psi ensures reliable integrity in rough handling under combat conditions. The momentary rearward impulse generated upon plug ejection should assist in overcoming the very small forward acceleration of the flamethrower which may result from a short lag of gelgas expulsion thrust behind the rise of CRR thrust. And the time required to expel the plunger from the fuel nozzle delays expulsion of fuel until pressurization transients have nearly passed, hence tends to produce a more nearly constant expulsion velocity (much as would a burst disc) and thus less deviation in point of impact.

Illustrative Example

To provide the basis for design of an illustrative unit, a capacity of 3 gallons of gelgas was selected as probably being adequate for the majority of fire missions without being unduly wasteful for smaller-requirement cases. Other characteristics of a flamethrower with an ideal range capability of ca. 100-150 yds. were taken from the design characteristics of the 10-gal. unit described in Section 2 above. The estimated weights of the components of the proposed 3-gal. unit are presented below in Table VIII and the configuration and other details are shown in Figure 13.

TABLE VIII

100-150 YD. DISPOSABLE ONE-SHOT FLAMETHROWER
RECOIL-COMPENSATED, SOLID PROPELLANT-ACTUATED

Estimated Weights

Item	Weight, lb.
Gasoline Gel, 3 gal. @ 6.25 lb/gal	18.8
Gasoline Tank, Steel/Al/Fiberglass (alternatives)	6.4/5.0/3
Gasoline Nozzle with Igniter	0.3
Polypropylene Piston	0.6
Subtotal	26.1/22.7
Counter-Recoil Rocket and Gas Generator:	
Solid Rocket Propellant (BF-122 Mod. 1)	0.85
Diluent-Coolant, NH_4Cl	0.45
Propellant Sleeve (Lam. Paper)	0.2
Motor-Generator Body Steel/Al/Fiberglass	1.4/0.8/0.6
Nozzle Insert (Injection-Molded Fiber/Phen.)	0.2
Diluent Supports (Lam. Paper/Phen.)	0.3
Subtotal	3.4/2.6
Miscellaneous Reinforcements	0.5
Firing Mechanism	0.3
Total Flamethrower Weight	30.3/26.1

Dimensions

Gasoline Tank (Hemispherical Ends)	ID 8.00 in.
	OD 8.20 in.
	Length 17.5 in.
Rocket/Gas Generator Unit	2.50 in. OD X
	15.0 in. Long
Overall Length	35 in.

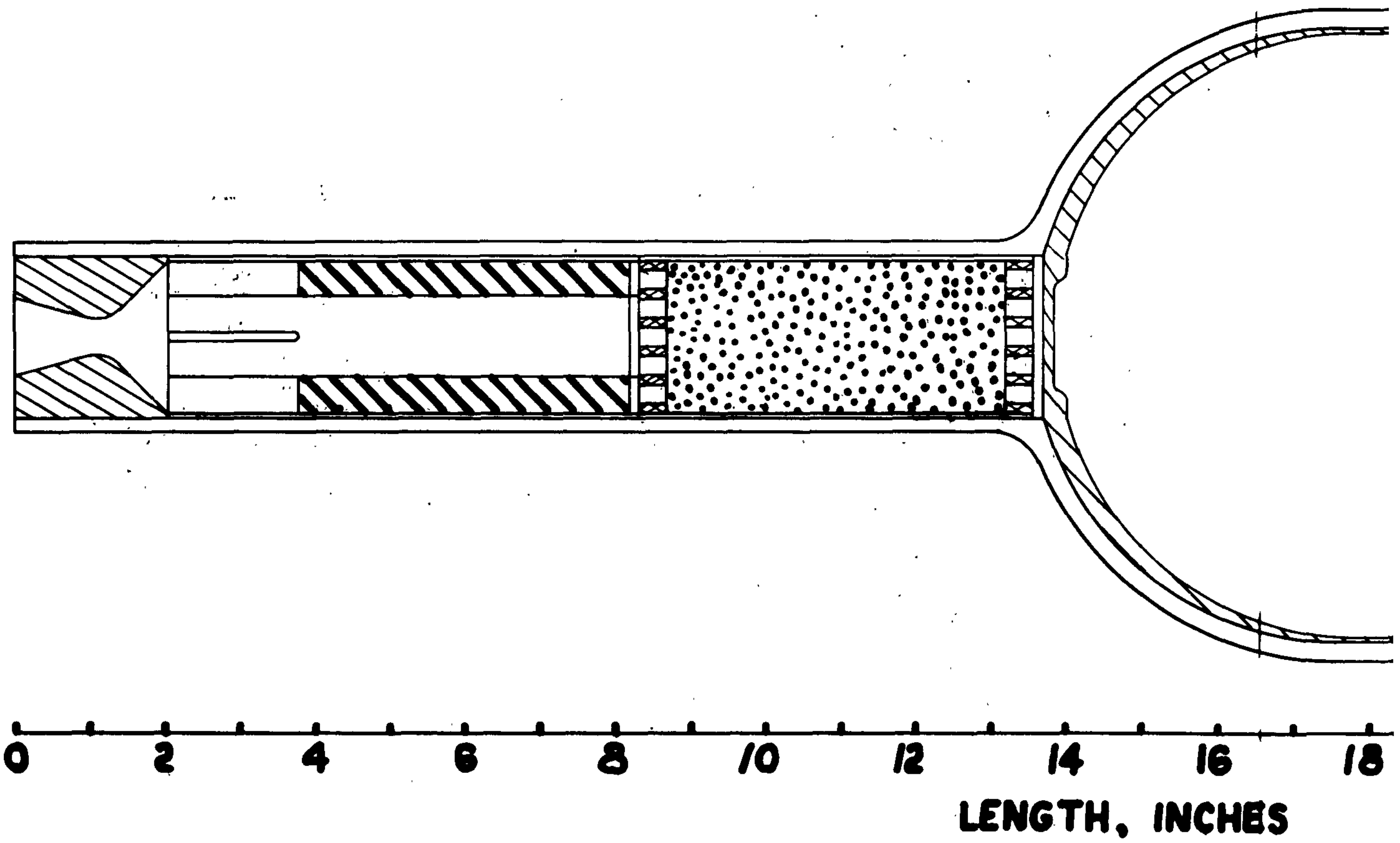
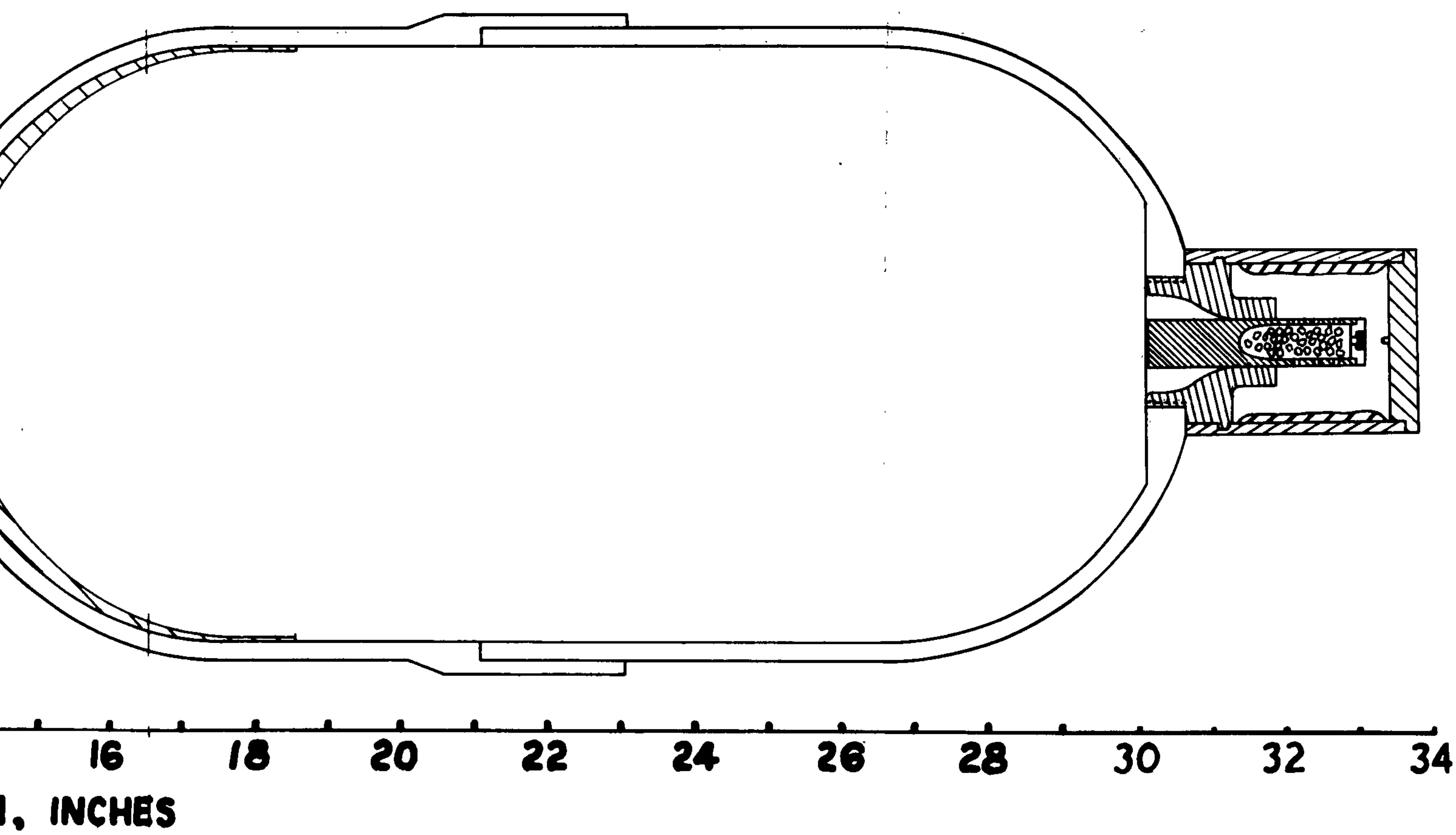


Figure 13 Expendable One-Shot Long-
Recoil-Compensated, Soli



Gasoline Capacity 3 Gal (19 lb)
Firing Time 1.5 Sec
Total Weight (est.) 28 lb.

endable One-Shot Long-Range Flamethrower
oil-Compensated, Solid Propellant Actuated

2

Features of Proposed Design

1. Extreme simplicity of construction and of use.
2. High reliability.
3. Solid propellant pressurization--no accessory compressors or gas generator vessels required.
4. Extreme one-man portability.
5. Instant readiness of all gelled fuel available.
6. High ratio of gelgas weight/total flamethrower weight (62-72% of total unit weight is gelgas).
7. Premixed, pre-packaged fuel gel with uniform, reproducible characteristics.
8. Unit forms its own shipping container.
9. Economical construction.

Discussion of Limitations and Advantages of One-Shot Configuration

It is considered probable that part of the reason for the 10-gal., 5-sec capacity requirement is to provide the opportunity to engage more than one target before having to disassemble and reload the unit (a considerably time-consuming operation). It may also have been intended, for long range shots, to provide the opportunity to correct an initial false aim by slewing the gun during expulsion ("hosing"). This technique is valid in the use of present-day flamethrowers, partly because of their longer firing time but especially because of the shorter ranges involved. However, in order to put a reasonable percentage of the fired fuel on a target at long range, it is essential to maintain the maximum possible fuel rod integrity. Any transverse deviations of the fuel rod from a straight line at launch will hasten the time of rod breakup (i.e., cause breakup closer to the operator, farther from the target); thus the curved rod which would result from hosing would likely have a significantly shorter range and different trajectory from the rod which would result from firing with a fixed point of aim. Therefore it is considered that the total fuel capacity would best be expended in a few individual bursts, each of which would be fired with as nearly constant a point of aim as possible. Thus each shot would be very similar to the firing of one solid propellant-actuated one-shot flamethrower. However, when the 10-gal. flamethrower fuel supply was exhausted, the unit would be out of operation for at least several minutes, which could be a disastrous period of time in combat.

In contrast to this, consider the case of a number of one-shot disposable units as described above, equivalent in weight to the loaded 10-gal. flamethrower with its associated quantity of reload supplies. One unit is fired with the operator's best estimate of allowances for range, wind, elevation, etc. If the target is missed, a second unit is fired immediately with corrections in elevation and azimuth. If on target, a large number of targets probably would be adequately neutralized with one 3-gal. hit. However, if more gelgas were required,

additional units could be fired in rapid sequence with such further minor aim corrections as might be indicated. Regardless of the quantity of gelgas required and/or the number of targets to be engaged, as long as any supply of gelgas is available at all, it is available in ready-to-use flamethrowers without the requirement for any reloading time, equipment, or personnel. Further, should a number of targets be required to be engaged either simultaneously or at multiple points, individual soldiers can use separate units, rather than requiring one team to transport one flamethrower from place to place; and in addition, a hit by a bullet or shell fragment upon one disposable flamethrower renders only that unit inoperable, and all other stores of gelgas on hand are still usable because each unit is its own flamethrower. In contrast, a hole in the tank, hose, or gun of the presently-envisioned 10-gal. rechargeable unit would render all available reload quantities of gelgas useless if no other flamethrower were at hand.

Another major combat advantage of the individual smaller units is the greatly increased portability and man mobility afforded by the smaller size and lighter weight. The presently-envisioned reloadable model without doubt will require a litter-type configuration with transportation by a two-man team. This presents a large, concentrated, highly conspicuous target and markedly reduces the team's ability to utilize such cover as is available--and impairs their running ability. However, with individual 27-lb units, presumably with rope or web handles bonded to the gelgas tanks, each man can carry one unit in each hand and run with scarcely-impaired speed. He can stay close to the ground, and take cover behind rocks or trees which will shelter only one man. Assuming the same two-man team, they can separate to present smaller dispersed targets, and if one man becomes a casualty, the entire flame-throwing potential is not eliminated. In addition, the two men now can carry 12 gal of gelgas vs. the 10 gal plus plumbing in the reloadable unit.

3.1.2 Workhorse Model Solid Propellant-Actuated Flamethrower

In order to carry out an experimental investigation of the concept of a solid propellant-actuated flamethrower (SP F/T), it was necessary to design and fabricate a workhorse model which would simulate as nearly as possible the operation of the conceptual model. At the same time, this workhorse model should afford the maximum feasible degree of flexibility in order to permit evaluation of various design alternatives, and should utilize fully any existing knowledge pertinent to this configuration.

The workhorse model is shown in exploded view in Figure 14. The tank was fabricated from 8.00-in. ID X 0.25-in. wall carbon steel tubing, with exterior lightening cuts except at the snapring grooves and wherever pressure taps were to be made. Endplates were made from

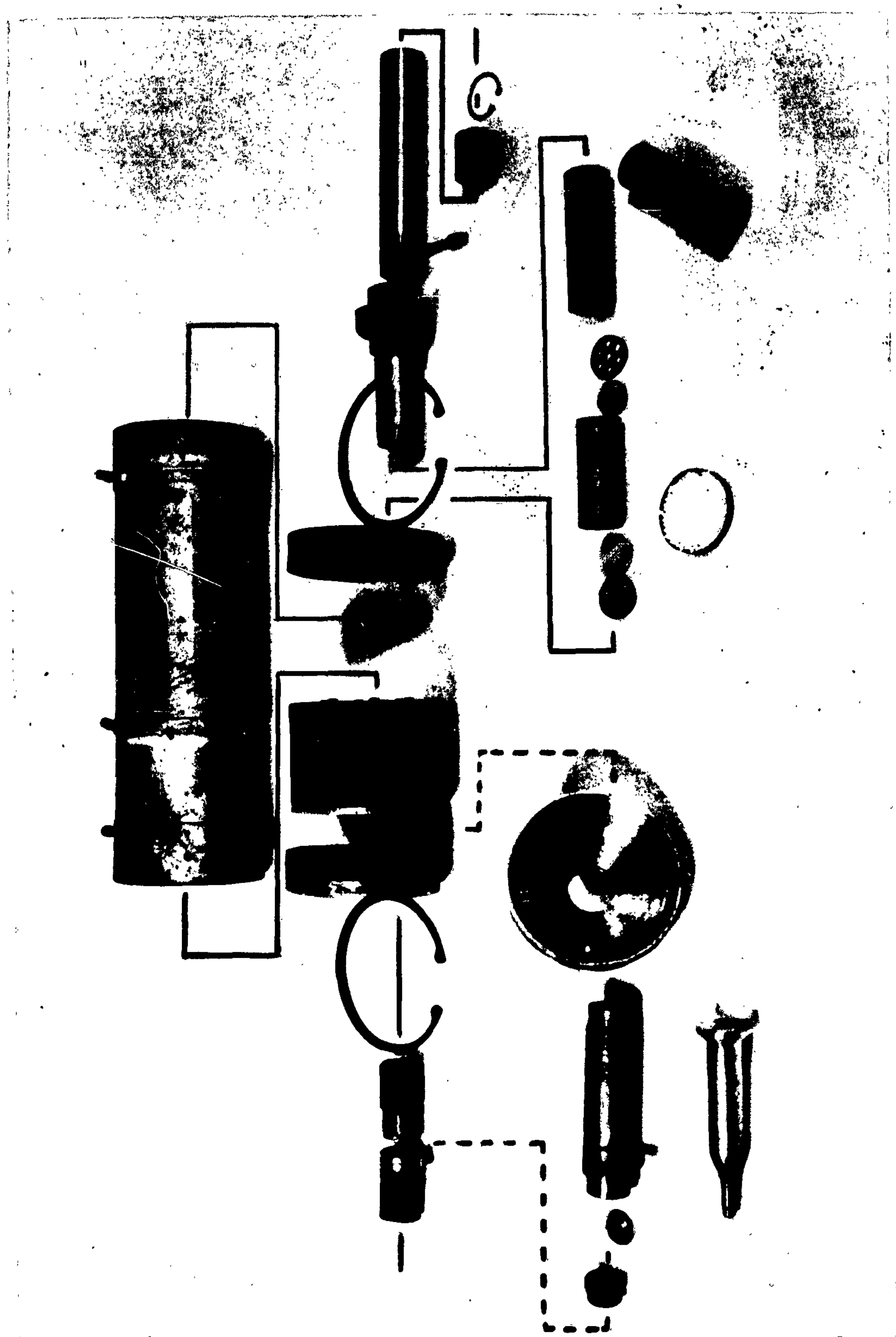


Figure 14. Exploded View of Workhorse One-Shot Solid Propellant-Actuated Flamethrower

2024-T4 plates 0.875-in. thick; seals were standard fabric-reinforced composition piston cups clamped by Panelyte* discs. The endplates were retained in the tank by internal snaprings. The piston also was fabricated from Panelyte sheet with internal cavities to reduce inertia effects; piston cups were used to seal against pressure from either side. The piston was made 5 in. long to minimize tendency to cock in the absence of a piston rod(which normally imparts transverse stability to a piston). A true piston effect is not expected to be required in the operational model; the bladder will provide sealing for all-attitude expulsion, and the plastic heat-shield cup should follow the collapse of the bladder. However, the absence of a bladder in the workhorse required the use of this rather bulky item.

The 0.50-in. diameter fuel expulsion nozzle of the government-furnished Flamethrower Research Device was adapted to the front endplate by means of a short coupling. Shown in front of this nozzle is the tube of a solid propellant flare used for fuel rod ignition; this is described in greater detail below in Section 3.2. At the right (rear) end of the tank is shown the counterrecoil rocket/gas generator (CRR/GG) assembly, which was made from 2-in. stainless steel pipe and a carbon steel pipe union. Below this are the components of the coolant/diluent bed--Panelyte end discs and ammonium chloride pellets--and dummy solid propellant grains. A copper rocket nozzle with its retaining ring completes the basic workhorse model. The complete unit is shown in Figure 15.

Also shown in the figure are two alternate components which were fabricated and tested later in the program. A conical (45° half-angle) converging tank end was made to provide a smoother transition from tank diameter to nozzle inlet diameter than did the original flat endplate; and a 0.625-in.-ID fuel expulsion nozzle was prepared to investigate the effects on rod stability, expulsion time, and recoil resulting from a larger nozzle. This nozzle was made geometrically proportional to the overall configuration of the 0.50-in. nozzle, including the overall straight inlet length, in order that the comparative performance be as nearly univariant as possible. The nozzle was fabricating by machining the desired contour on the outside of an aluminum mandrel, where it was convenient to blend and polish surfaces; this mandrel was then positioned in the 2-in. pipe housing, and a low-melting alloy was cast around the mandrel to form the nozzle. This nozzle also was provided with a burst disc retainer at the front end to evaluate the effect of a more nearly constant expulsion pressure-time characteristic upon rod stability and dispersion.

* Trademark of Thiokol Chemical Corp., proprietary laminated paper/phenolic structural board.

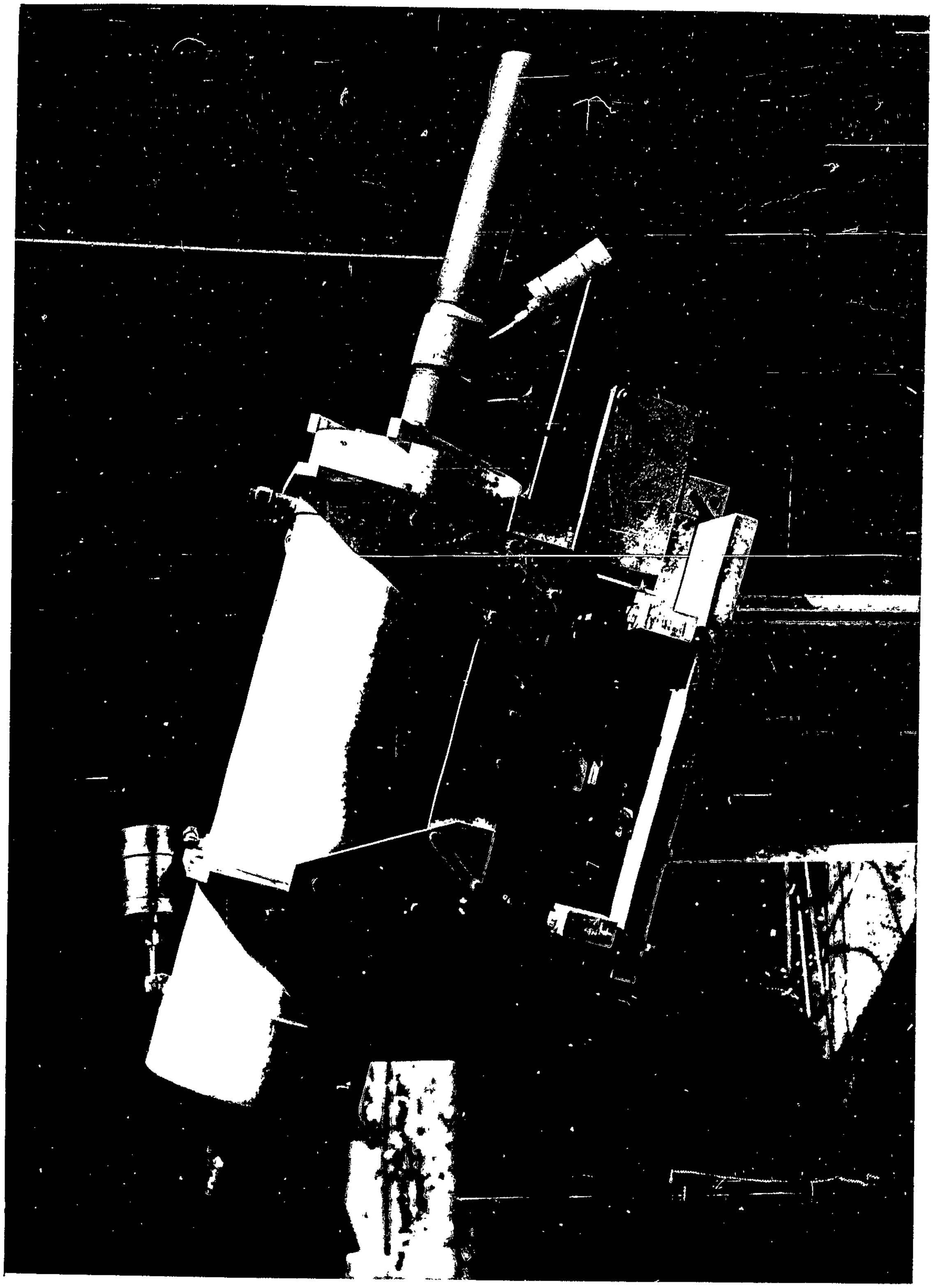


Figure 15. Workhorse Solid Propellant-Actuated Recoil-Compensated Flamethrower on Flexure Thrust Mount

A total of 40 solid propellant CRR/GG grains was prepared from two propellant batches. These grains were of slotted-tube configuration; viz., an 8.50-in. long circular tube 1.06 in. ID X 2.00 in. OD, with four radial slots 0.12 in. wide x 3.00 in. long spaced at 90° running entirely through the propellant web at one end of the grain (the aft end). These grains could be trimmed on both ends to provide varying amounts of burning area, and also burning area-time profiles which either increased, remained constant, or decreased during the burning time. The propellant was cast and casebonded into Panelyte paper/phenolic tubes 2.00-in. ID x 0.06- in. wall. The grains were expected to have a burning time of approximately 1.4 seconds at 500 psia chamber pressure. The nominal composition of this propellant is shown in Table IX below.

TABLE IX

BF-122 MOD I PROPELLANT--NOMINAL COMPOSITION

Ingredient	Weight Per Cent
Ammonium perchlorate (special coarse)	57.40
Ammonium perchlorate (fine ground)	24.60
LP - 205	11.51
LP - 33	5.00
Paraquinone Dioxime	1.12
Sulfur	0.08
Benzyl mercaptan	0.04
Magnesium oxide	0.25
	100.00

Since fuel rod considerations were not an important facet of this contract, no major effort was to be exerted in this area. However, rod ignition was necessary for many of the test firings in order to obtain a correct view of the effects of various parameters upon F/T range. The use of chromyl nitrate introduced certain operating problems which it would be preferable to avoid if possible. In addition, it was desired to take at least a cursory look at the use of a solid propellant igniter for the fuel rod, since if this were feasible it would contribute significantly to the simplicity and practicability of the SP F/T concept. The selection of a composition for the experimental solid propellant fuel rod igniter (SPFRI) was based on the following considerations.

The reduced volatility of the more heavily-thickened F/T fuel required for long range had resulted in undependable ignition by conventional pyrotechnic matches, and even by a row of propane-air flames. This had led to the investigation of chromyl nitrate as a hypergolic igniter for on-off-on multiple-shot operation. For a one-shot device, the complexity of handling small quantities of a second liquid, especially

a reactive one, was highly undesirable. The ineffectiveness of the propane-air flames might well have been due to relatively slow convective heat transfer through a low-conductivity gas film, especially with opposing mass transfer from the rod as the first bit of vapor began to evolve. However, if sufficient numbers of small incandescent particles could be made to impact the fuel rod, they would perforce penetrate the low-conductivity film and transfer their sensible heat directly by conduction to the fuel which it was desired to vaporize. Heavily-aluminized composite rocket propellants were known to generate large weight percentages of very hot, fine solid particles. In addition, these propellants had been shown to be insensitive to impact, heat, and temperature cycling, yet capable of rapid ignition from a proper source and of reliable combustion at atmospheric pressure. Therefore this seemed a logical starting point for a SPFRI composition.

In order to optimize the formulation for maximum enthalpy in the solid phase, theoretical calculations were run as for a rocket engine operating at a chamber pressure of 25 psia expanding to sea level, and the ratio of Al to oxidizer (ammonium perchlorate) was varied over a wide range. Binder (polyisobutylene-acrylic acid copolymer, PBAA) content was fixed arbitrarily at 12% in order to provide a very stiff mix which would not sag or slump before curing if not supported by a mandrel (an undesired complexity for this unsophisticated item), yet still be plastic enough to afford a coherent, sticky consistency which could be rolled or pressed into place. The significant results of this brief study, viz. total weight per cent solids and expanded temperature of the combustion products vs. per cent Al, are plotted in Figure 16. Since maximum solids and maximum temperature nearly coincided at 25% Al, this composition was an obvious selection.

3.2 Solid Propellant-Actuated Flamethrower Test Program

The program of testing for the workhorse model solid propellant-actuated flamethrower (SP F/T) was intended to accomplish the following major objectives:

1. Demonstrate the use of a single solid propellant grain both to provide CR thrust and simultaneously to provide pressurization of the flame fuel tank to accomplish expulsion.

2. Determine the nature, magnitude, and degree of synchronization of R vs. CR transients during the ignition phase of flamethrower operation. (It was recognized that this workhorse unit would not permit exploration of shut-down transients because of the absence of a blowout port in the piston, as would be found in the operational prototype). Thus at the end of expulsion in the workhorse unit, the 3-gal. fuel tank volume would be pressurized to approximately 450 psig; this could vent only to the rear through the CRR/GG upon burnout of the solid propellant grain, which would result in a large forward thrust at end of expulsion,

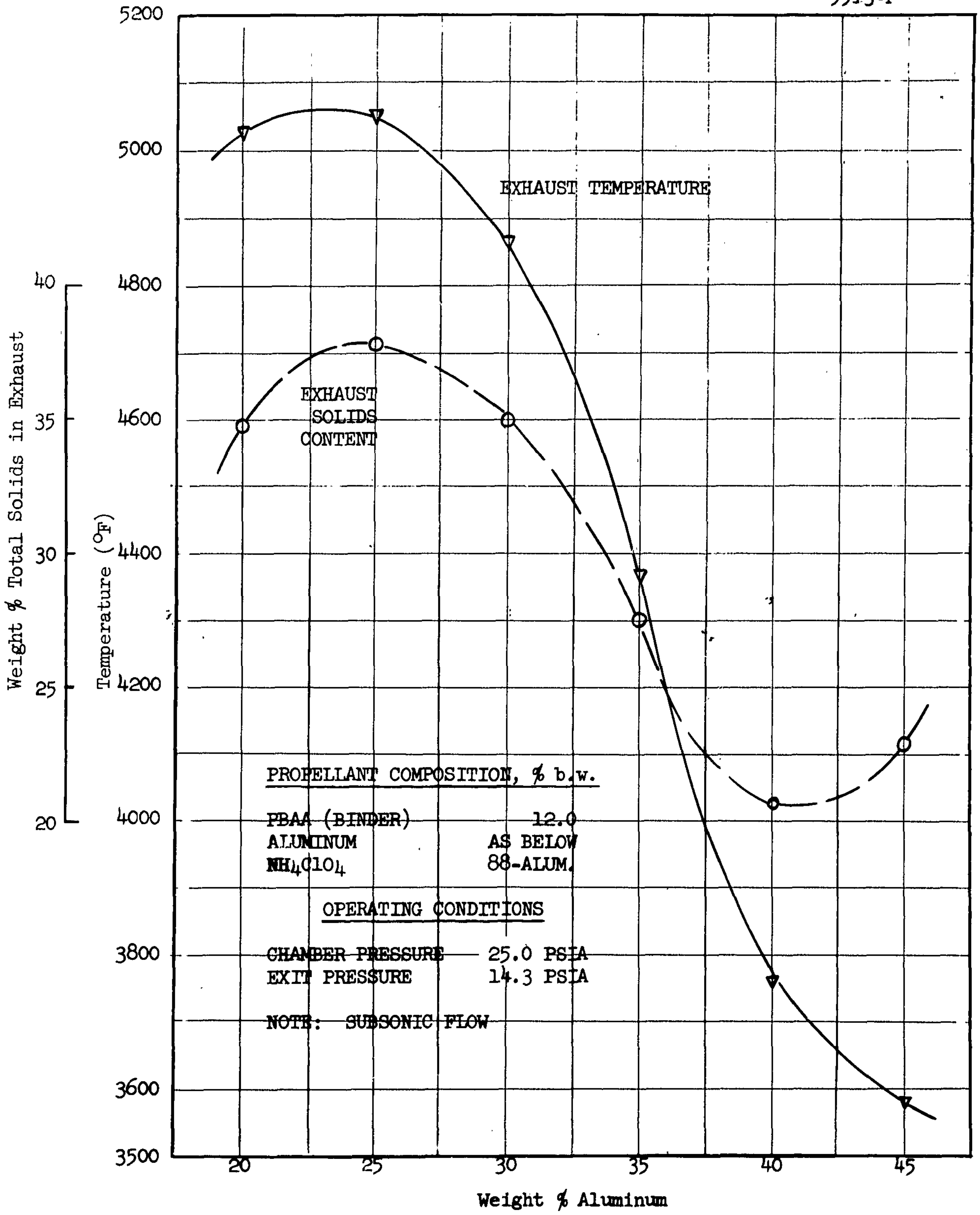


Figure 16. Solid Propellant Igniter for Fuel Rod, Exhaust Parameters vs. Composition

followed by a slow decay of pressure and thrust.

3. Evaluate the effectiveness of a heavily-aluminized composite solid rocket propellant as an igniter for the fuel rod in comparison with the use of chromyl nitrate for chemical ignition.

4. Investigate the use of pelleted ammonium chloride (NH_4Cl) as a coolant/diluent for the portion of CRR/GG propellant gases which flow forward to pressurize and expel the flame fuel.

5. Investigate attainable range vs. pressure and flamethrower elevation.

3.2.1 Preliminary Tests

Before commencing the major tests outlined above, several minor details had to be attended to first. These details, which are encountered in the development of any new solid propellant rocket motor, included the determination of the proper size of rocket igniter charge, determination or verification of propellant burning rate as a function of pressure, validation of the effects of grain design upon pressure-time characteristics, and (especially in such small motors) verification of propellant specific impulse and characteristic exhaust velocity (c*).

The igniter chosen for use with the workhorse flamethrower was not necessarily characteristic of the type which would be used in an operational model. However, it has been found to be extremely flexible and convenient for use in experimental programs. This igniter consisted of an electrically fired M2 squib (National Northern Division, Atlantic Research Corporation) and a booster charge of pyrotechnic pellets (Ordnance Products Company, Cockeysville, Maryland) assembled loosely in a small polyethylene-film bag. This igniter is positioned in the central perforation of the grain at the head end (i.e., the end opposite the nozzle) where it is secured with a piece of masking tape. The leads are brought down through the central perforation of the grain and out through the rocket nozzle. In experimental firings, where weather conditions may not constitute a problem, the rocket nozzle may or may not be closed or obturated. However, since such obturation tends to enhance uniformity and reliability of ignition, and in any case an operational unit would be obturated to provide weather protection, it was decided to obturate the nozzle of the CRR/GG by means of a small cork. Each cork was rolled vigorously to soften and render it more pliable, then was notched longitudinally with a knife to provide a channel for the squib wires, and inserted into the nozzle throat from the inside until the larger end of the cork was nearly at the nozzle throat. Igniter tests with a dummy grain indicated that a minimum of 5 g of the aspirin-sized pellets would be required to develop adequate ignition pressure. However, initial firings with a live propellant grain showed that a minimum of 7 g of aspirin-sized pellets was required to achieve ignition, and that 9 g gave faster and more uniform ignition. Accordingly, the 9-g charge was standardized for the rest of the test program.

No attempt was made to optimize this igniter by means of varying the size of the pyrotechnic pellet, in order perhaps to reduce the weight of the pyrotechnic booster charge. As long as reliable ignition was being accomplished, no further refinement of the igniter was required in this research program.

Next it was necessary to characterize quantitatively the rocket operating parameters of this propellant and motor configuration. The propellant selected for this program (which had been used by RMD for another program in an engine of different configuration) was a minor modification of a classified formulation which had been characterized quite thoroughly in much larger motors; but precise determination of the characteristics of the modified composition had not been made. Furthermore, whenever propellant is made in small quantities for experimental applications, the high degree of reproducibility attained in production quantities is not necessarily realized, and such small lots should be checked out individually. Accordingly, three firings were made with the motor operating as a conventional rocket engine to obtain these operational parameters. The motor used was a CRR/GG motor tube of the workhorse flamethrower, modified by the installation of a plug at the head end to prevent forward flow of the propellant gases. (This same configuration was used in the igniter tests described above). Firings were made with essentially identical grains and three different nozzles; the results are tabulated in Table X. The quantities of primary interest--burning rate, K_n, and specific impulse--are tabulated, along with other operational parameters and the definitions of all quantities involved. From these tests, the burning rate (that parameter exerting primary control over rocket operation) was found to be approximately 10% lower than postulated. The measured values of all other operational parameters appeared to be consistent with the observed burning rate.

Following the performance tests described above, which were performed on a standard rocket thrust mount in an existing rocket test stand, three firings were made on the flexure thrust mount which was fabricated for testing the workhorse flamethrower, to evaluate the effect of grain geometry upon pressure-time profile. This flexure thrust mount was installed on the machine-gun tripod which was supplied as part of the government-furnished Flamethrower Research Device. Although the tripod was anchored securely to the floor by means of a turnbuckle, the thrust traces indicated that the overall suspension system was deflecting as a relatively low force-constant spring. Apparently, the tubular legs of the tripod, which were positioned at a very obtuse angle in order to provide minimum height of the flamethrower, were primarily responsible. It is axiomatic in measurement of solid propellant rocket thrusts of short duration, that the thrust mount be as rigid as possible. This confines the amplitude of mechanical vibrations of the system to the limits of load-cell deflection, which are small. Thus, the small amplitude vibrations contain little energy, and quickly die out. Such was not the case, however, for the tripod-mounted test system. The recorded thrust trace was found to contain large oscillations which prevented precise determination of rocket thrust. Fortunately the pressure trace, which was of prime interest, was unaffected and satisfactory pressure data were obtained. The results are summarized in Figure 17.

TABLE X

SOLID PROPELLANT (BF-122 MOD. I) ROCKET CHARACTERIZATION

	Test No. 2AX-		
	5213	5214	5215
Grain burning area, in.^{2}	29.5	29.5	29.5
Propellant weight, lb	.849	.847	.853
Throat diameter, in.	.471	.402	.525
Propellant/throat area ratio, K_n	169.3	232.4	136.3
Expansion ratio, A_e/A_t	5.76	8.66	4.53
Average run pressure, P_{ch}, psia	442	765	302
Average run thrust, lb	104.9	138.2	85.3
Web burning time, t_b, sec	1.556	1.285	1.861
Action time, t_a, sec	1.654	1.335	1.955
Burning rate, in./sec	.292	.354	.244
Delivered I_{sp}, sec	201	216	192
Characteristic exhaust velocity (ft/sec)	4749	4853	4741
Thrust coefficient, C_F	1.363	1.422	1.306

Definitions:

Propellant/Throat Area Ratio, K_n: The ratio of propellant burning area to nozzle throat area; when plotted vs. average pressure on a log-log plot, useful for choosing nozzle throat size for a given grain or for selecting grain size for a given nozzle, to obtain a desired P_c.

Expansion Ratio, A_e/A_t: The ratio of nozzle exit plane area to throat area.

Definitions:

Average Run Pressure (Thrust):	Calculated by dividing the planimetered integral under the pressure (thrust) vs. time trace by the action time, with proper calibration factors.
Propellant Web:	The minimum thickness of propellant which must be burned through.
Web Burning Time, t_b:	The time beginning when the pressure has risen to 10% of maximum chamber pressure and ending at web burnthrough.
Action Time, t_a:	The time beginning when pressure has risen to 10% of maximum chamber pressure and ending when pressure falls to 10% of maximum champressure.
Integral of Pressure (Thrust) vs. Time:	The integral of pressure (thrust) during the action time.
Delivered Specific Impulse I_{sp}:	The integral of Fdt divided by the weight of propellant burned.
Characteristic Exhaust Velocity, c*:	The quotient of the integral of Pdt multiplied by the gravitational constant and the nozzle throat area divided by the weight of propellant burned.
Thrust Coefficient (of Nozzle):	The quotient of the integral of Fdt divided by the product of the nozzle throat area and the integral of Pdt.
Burning Rate:	The quotient of the propellant web thickness divided by the burning time.

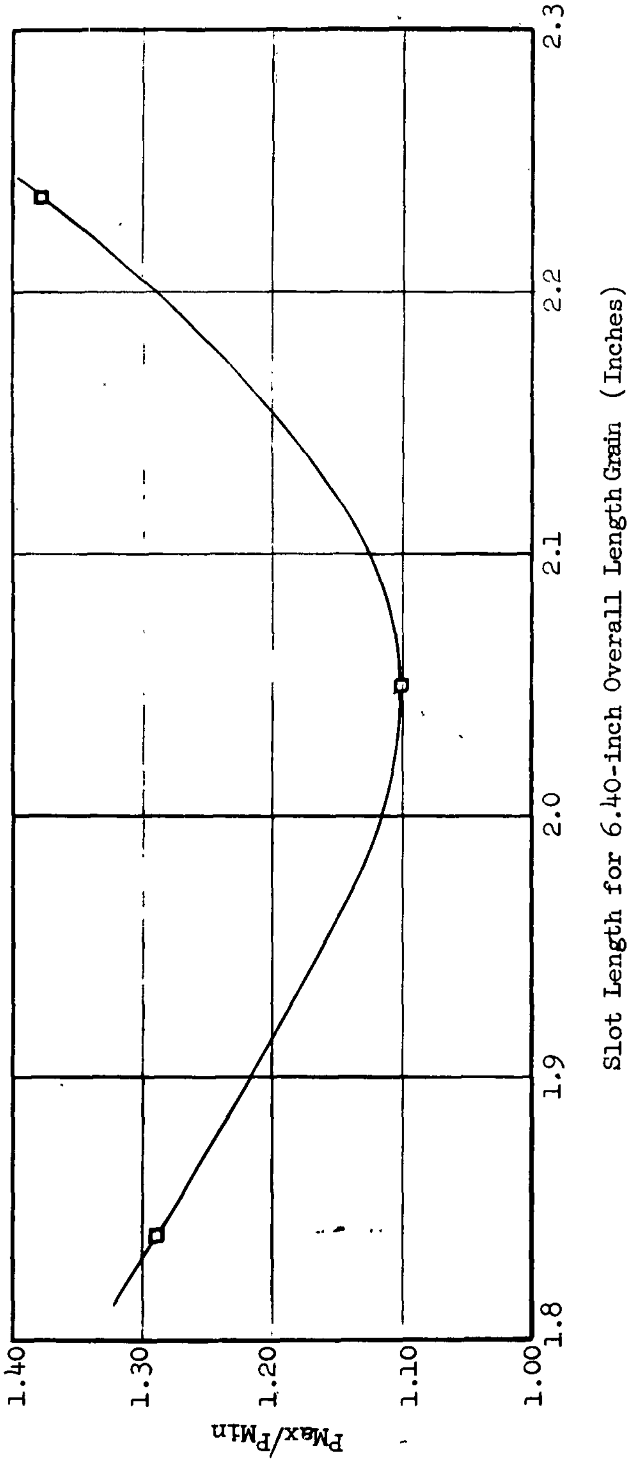


Figure 17. Effect of Grain Geometry on Pressure Variation in Rocket Motor Firings

which is a plot of the ratio of maximum to minimum chamber pressure during steady-state operation vs. the length of slot in a 6.40-in. long grain. This plot indicated that an optimum slot length was approximately 2.025 in. for this overall grain length.

Following the geometrical checkout, two firings were made for a preliminary evaluation of the effectiveness of the coolant/diluent bed, and also of the pressure drop across this bed with hot-gas flow. Earlier flow tests had been made with cold gas at corresponding volumetric rates, and had shown pressure drop across the bed to be less than one psi with pellet sizes of 1/8 to 1/4-inch diameter (length equivalent to diameter). For this test, a series of bare small-wire thermocouples were connected in parallel and installed across the flow channel to average out the gas temperature. In the first test a peak temperature of approximately 980° F was recorded with a pressure drop across the bed of 78 psi. However the Panelyte tube which contained the coolant bed clearly showed evidence of substantial hot gas flow around the outside of the tube as well as through the coolant bed. The coolant bed itself was found to be compacted and/or fused into a porous but substantially continuous mass. All thermocouples appeared intact after this test. The second firing in this series used 1/8-inch diameter pellets and indicated a maximum temperature of 1780° F with a pressure drop across the bed of 27 psi. However, again in this test the coolant bed showed evidence of substantial bypassing and all but two of the thermocouples were burned, fused, or blown away. The condition of the coolant bed and the substantial amount of bypassing indicated that weight-loss measurements of the coolant would be highly inconclusive, and it was intended to make further gas temperature measurements later in the firing series. A checkout test of the overall system was performed by expelling water from the flamethrower in place of fuel gel, and a barely discernable rise in tank temperature indicated that sufficient cooling was being accomplished. Unfortunately, the press of time in subsequent experiments prevented further temperature measurements, and the final resolution of the quantity and configuration of coolant needed--and the degree of cooling actually required--remains to be determined. Actually, the degree of cooling required will be a function of the particular operational model selected, and thus appropriately should be determined for a specific system. The weight and volume of the coolant bed constitute a small fraction of the overall operational configuration in any case.

3.2.2 Chromyl Nitrate Ignition Tests

Initial firings of a recoil-compensated flamethrower were made with the solid propellant-actuated unit; chromyl nitrate was used to ignite the fuel rod. Mr. Werner Beyth of CRDL, Contract Project Officer for this program, was present to witness the firings and to assist in set-up of the hypergolic igniter device. The first shot (FTXS-11) apparently failed to achieve impingement of the chromyl nitrate stream upon the fuel rod, since the entire rod was expelled unignited. The fuel was deposited in a series of reasonably uniform-sized "blobs" or lumps at ranges from 10 to 65 yards from the flamethrower, with lateral dispersion of about ±1 yard. To verify the activity of the chromyl nitrate, a drop of residual material from the hypodermic syringe was allowed to fall upon one of the portions of expelled fuel shortly after the test. Upon contact, the entire surface of the "blob" was immediately ignited by a vigorous flash. Pertinent data from this and subsequent solid propellant-actuated firings are summarized in Table XI.

The second test (FTXS-12) achieved ignition of the last two-thirds of the rod, but the first one-third (estimated) was unignited. The drive motor of the chromyl nitrate ejection device was started about 1 sec before firing the SP F/T; but apparently, insufficient time was allowed for the ignition system to come up to full flow, or else transient startup vibrations generated sufficient oscillation of the hypodermic needle to cause the chromyl nitrate stream to break up and/or miss the initial portion of the fuel rod.

Subsequent to these tests, it was found that several of the horizontal lengths of stainless steel tubing of the liquid propellant F/T system inside the test turret had developed large numbers of pinholes. Apparently, HCl from the solid propellant exhaust had dissolved in droplets of condensate on these lines and corroded the lines, despite operation of an exhaust fan during and after each firing. Therefore, a new, rigid pedestal mount was prepared outside the turret and the SP F/T was operated from there for all subsequent tests. No further difficulty was encountered with stainless lines inside the turret.

3.2.3 SPFRI Development--Pressurization Booster Charge

The next five firings (one of which was abortive) of the SP F/T were conducted principally to evaluate the effectiveness of the solid propellant fuel rod igniter (SPFRI), and also to investigate the use of a thin wafer of solid propellant as a "booster charge" to enhance the rate of pressure rise in the system during the ignition transient. This initial period during which pressure rose from ambient to steady-state expulsion pressure was undesirably long, due to the initial void volume of the CRR/GG and void volume (ullage) in the fuel tank behind the piston, plus the increasing volume generated as the piston moved forward. As a result, expulsion of the

unrestrained fuel gel began almost immediately at low velocity, and expulsion velocity then increased continuously until constant velocity was reached. This caused the deposition of a significant portion of the fuel load at varying ranges short of the main impact area of the fuel discharged at steady-state conditions, and masked the steady-state deposition area.

This slow rise of pressure can be seen in the pressure traces of Figure 18, which were made in subsequent firings, and compared with the more desirable type of trace obtained in firing FTXS-23, shown in Figure 19. (Note that in none of the firings shown in the illustrations cited were any booster wafers used; the shape of the curves was the important point, by whatever means obtained.) Since the CRR/GG grain was capable of maintaining steady-state pressurization once this had been obtained, what was needed was some means of providing an initial significant increase in burning surface which would decrease smoothly toward zero (leaving the basic CRR/GG grain operating) as steady-state conditions was approached (i.e., a highly "regressive" area characteristic). A brief analysis of the burning area-time behavior of slices of surplus propellant cut from the ends of CRR/GG grains indicated that slices from the slotted end, inhibited on one face, would provide the desired area-time profile. Various degrees of regressivity could be obtained as a function of burning time (slice thickness).

Three slices nominally 0.1, 0.2, and 0.3 in. thick were prepared and tested in F/T firings (FTXS-13, -14, and -15). The last of these failed to yield usable information because the run aborted (as discussed below). Accordingly, a 0.3-in. slice also was used in tests FTXS-16 and 17 which were made on the same day. Instrumentation difficulties caused the loss of quantitative pressure data on these latter tests. However, it was possible to conclude that significant steepening and shortening of the rise time was obtained by this approach. In an operational model, of course, this booster effect could be obtained simply by grain redesign, which was not feasible to do in the prototype. Unfortunately, little if any reduction in longitudinal dispersion was demonstrated in these firings, and thus this complexity was eliminated from subsequent firings.

Returning to the prime purpose of this series, the solid propellant fuel rod igniter (SPFRI) proved to be a solid success. The first SPFRI was a rather crudely-fabricated prototype for initial evaluation of the concept. It consisted of a piece of 2.00-in. ID X .062-in. wall Panelyte tubing lined with a layer of the optimized 12 PBAA/25 Al/63 AP propellant ca. 0.12 in. thick x 6 in. long. This 6-in. length was considered to be greatly in excess of that required for ignition; but it was desired to achieve a positive indication of ignitive capability on this first test (FTXS-13), if possible, and then to cut back to optimum dimensions on later tests. Because of the short burning time (and unverified burning rate) of this thin layer of propellant, it was ignited (by the same type of igniter used for the CRR/GG grain) simultaneously with the CRR/GG. Camera coverage included a 1000 frame/sec camera including the SPFRI and approximately 10 ft. of initial fuel rod trajectory, to study the ignition function; and a 48 frame/sec documentary camera which encompassed the first 50 yards or so of fuel rod

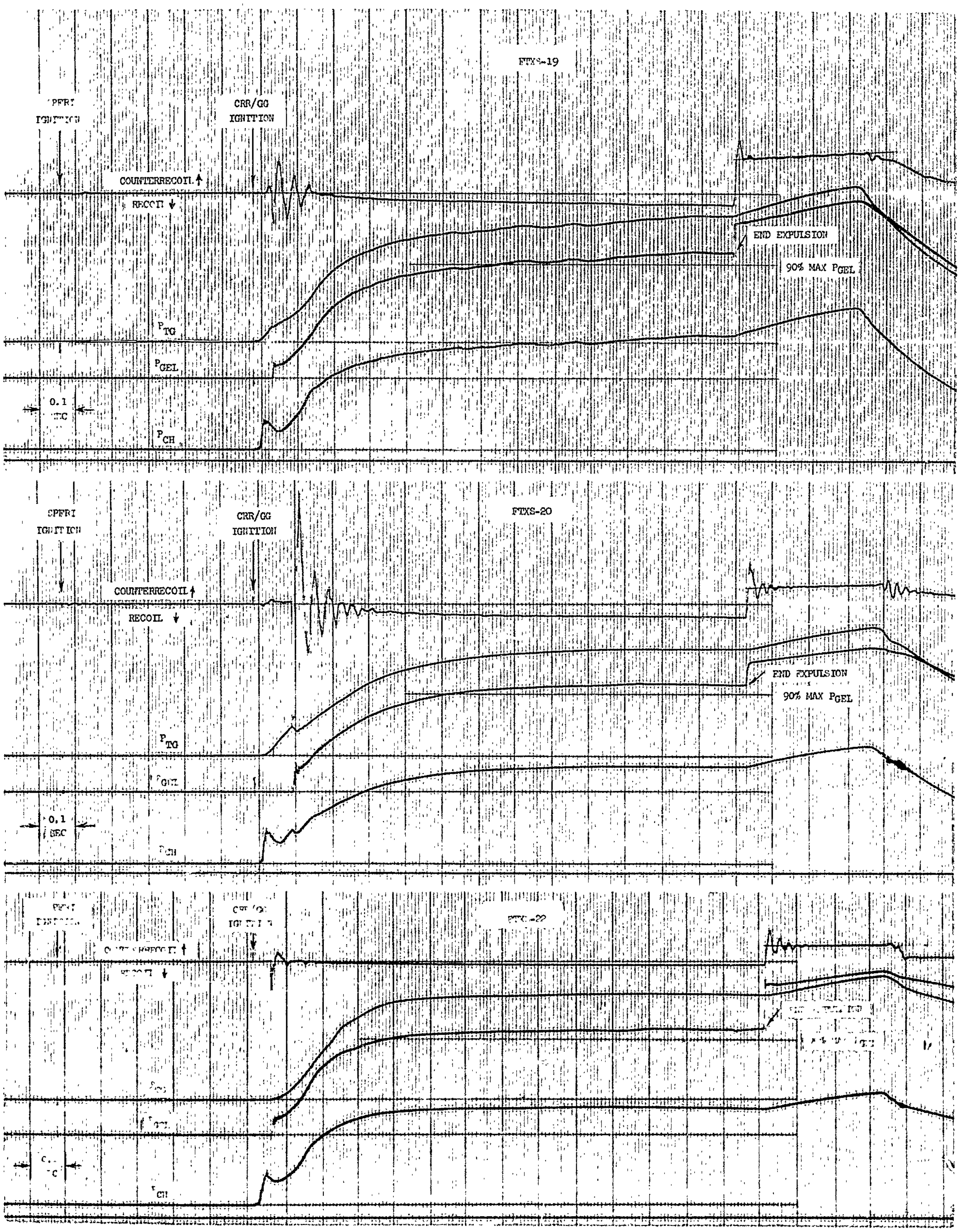


Figure 18. Solid Propellant-Actuated Flamethrower Firing Records With 0.500-inch Fuel Nozzle

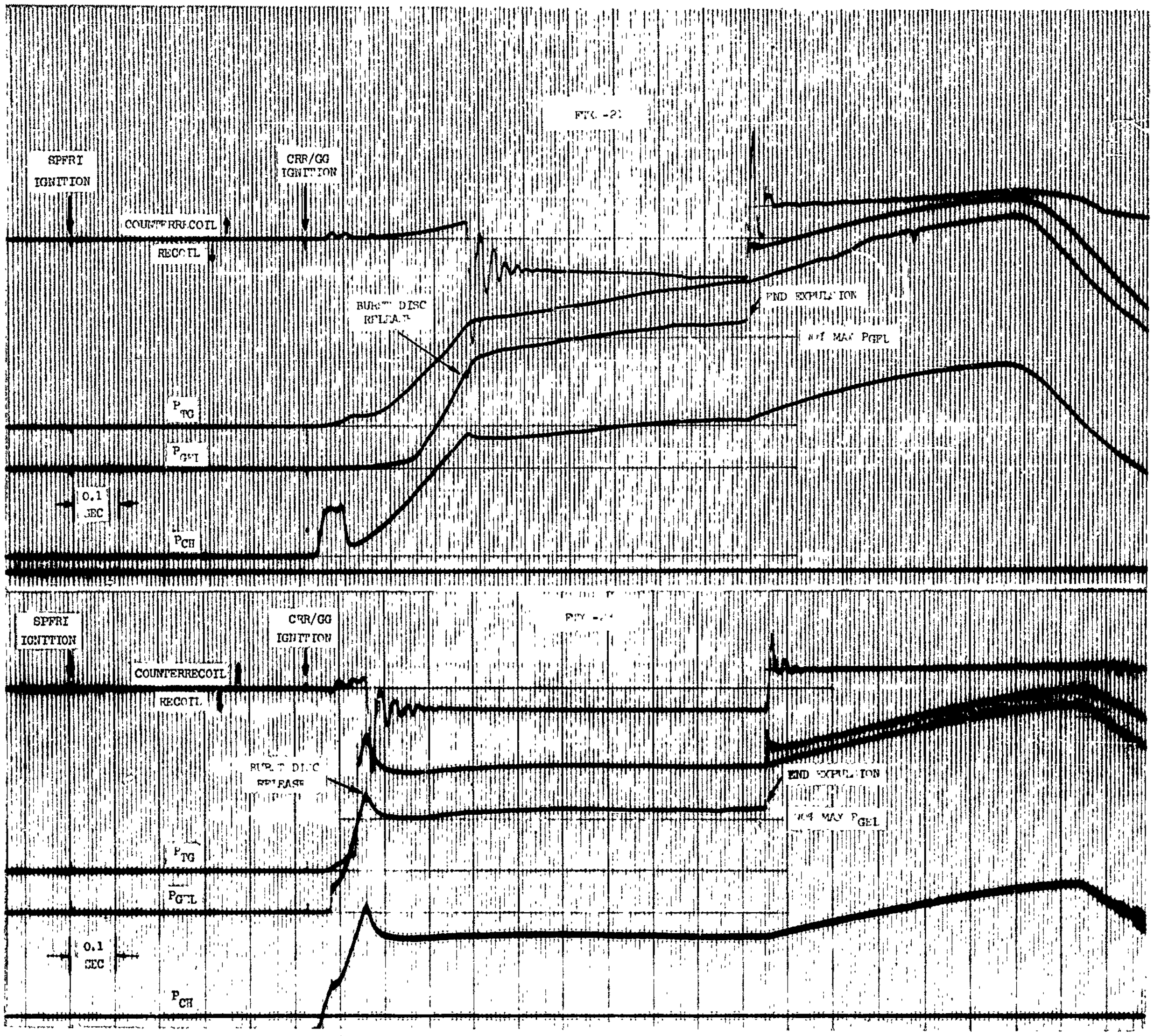


Figure 19. Solid Propellant-Actuated Flamethrower Firing Records

With 0.625-inch Fuel Nozzle and Burst Disc Fuel Restraint

trajectory, to ascertain whether fuel rod breakup occurred within this distance with this SPFRI which was expected to produce rather vigorous ignition.

The photo records indicated that some fuel apparently was deposited in the SPFRI very shortly after SPFRI ignition, before the fuel rod emerged from the smoke cloud, which extended ca. 6 ft. in front of the mouth of the igniter tube. A bushy, vaporous flame billowed in front of the SPFRI. Then the fuel rod emerged from the smoke cloud, and the front end clearly was bent double and trailed a slower, broken section which was being left behind; this first portion (a few feet long) was unignited. Very shortly thereafter, ignited fuel rod emerged from the cloud and the run assumed nearly steady-state condition. However, throughout fuel rod expulsion, the ten feet or so of ignited rod within the picture was surrounded with a sheath apparently of burning vapor that was several inches to nearly a foot in diameter; no flame could be seen inside immediately on the surface of the rod, which could often be seen inside this flame zone. The conclusion was reached that thisSPFRI was supplying so much heat to the fuel rod that it was vaporizing far more than enough fuel to achieve ignition; and the excess vapor was preventing diffusion of air to the vicinity of the fuel rod surface (at least for that portion of rod within the field of view) so that the surface could ignite. Apparently, farther downrange and out of camera view, as the excess vapor was consumed, combustion ultimately reached the rod surface, where it then continued. Relatively heavy deposition of 4-12-fluid oz. (estimated) blobs of fuel occurred between 90 and 110 yards, with diminishing depositions down to 60 yards and out to a maximum of 127 yards. A very few small scattered deposits were found around the 20 and 40 yard stakes. Occasional unignited blobs were found scattered throughout nearly the entire impact pattern. Lateral dispersion was approximately ±2½ yards, with wind of ca. 3 mph bearing approximately 240° to the firing direction.

The Statham dynamometer was damaged during this test, apparently by the transient recoil thrust generated when the ignition obturation cap blew off the SPFRI at ignition. This cap, which consisted of a 2-in. diameter plate of Panelyte 0.375-in. thick, was secured to the SPFRI only by 1½ wraps of 1-in. wide masking tape. However, a 100-lb preload had been applied to the thrust mount in the recoil direction in order to minimize thrust trace oscillation; and apparently at least 60-70 psig developed in the SPFRI before the igniter cap blew off. Over the 2-in. diameter (3.14 sq. in.) of the SPFRI, this could generate an additional 200-lb. of force, which exceeded the 50% allowable overload of the Statham.

The second SPFRI (used in Firing FTXS-14) was essentially identical to the first, except that the length of propellant was reduced from 6 in. to 3 in. High speed photographic records showed that extremely vigorous and continuous ignition of the fuel rod was again achieved, except for a very short cold (unignited) tip. Subsequent tests used more refined SPFRI's which had smooth propellant surfaces. These could be expected to give more reproducible flow rates of combustion products. However, the flow rate per unit length of igniter (all igniters had the same nominal cross-section) could be expected to be somewhat lower than that of the earlier SPFRI's because the smooth-surfaced igniters presented less burning surface than the first, highly irregular-surfaced models. Accordingly, a 3-inch long, smooth SPFRI was used in Test FTXS-15 to verify that this length would still provide more than adequate ignition at the lower flow rate. When this firing proved abortive, as described subsequently, the 3-inch length was retained for Tests FTXS-16 and -17, where vigorous ignition also was obtained.

Test FTXS-15 was intended to evaluate the first smooth-surfaced SPFRI, as noted above; and also to explore the effect of using an oversized cork inside the fuel expulsion nozzle to delay expulsion until fuel pressure had risen at least nearly to steady-state level. Unfortunately the cork was too large and caused an indefinite delay; neither cork nor gel was expelled. Thus the effectiveness of the refined igniter could not be determined in this firing; and since all conditions were non-standard, the data would have little significance and are not reported.

Tests FTXS-16 and -17 were essentially duplicate tests continuing the SPFRI investigation and the development of the pressurization booster grain. Both tests used 0.3-in. thick booster wafers, and rapidity of pressurization was still further improved. Instrumentation difficulties prevented obtaining gel pressure data, but gas pressure data indicated that pressurization (and hence, expulsion) was normal. The Contract Project Officer, Mr. Beyth, commented that the behavior of the rod in flight, breakup, and impact pattern were normal for a ½-in. diameter fuel nozzle fired to extreme range.

The final series of firings all used SPFRI's which had 2-in. propellant lengths. In all cases, ignition of the rod was at least fully adequate, and may have been still somewhat excessive. It should be noted that this last series included firings of gels which had been in the unprotected workhorse SP F/T for 16-20 hours or more at ambient temperatures between 10° F and 0° F or lower. One such firing (FTXS-20) is shown in the frontispiece, Figure 1. At no time has the SPFRI failed to achieve ignition of the fuel rod.

In all SPFRI firings after the first (FTXS-13), a time delay relay was used to permit ignition of the SPFRI approximately 0.5-1.0 sec prior to the CRR/GG (and hence, prior to expulsion). This was done to ensure

that the SPFRI had reached steady-state operation, since some of the high-speed movies of ignition had shown that the rate of efflux of combustion products from the SPFRI increased markedly some time after expulsion had begun. It has not been satisfactorily resolved whether this is in fact due to deposition of some fuel gel from the slow-moving rod tip, as has been postulated. The degree of obturation of the SPFRI has been substantially less than that expected to be used in the operational model, and no effort has been expended to refine the ignition charge of the SPFRI. Therefore, it may not be reaching full performance as promptly as desired. However, motion pictures show that all SPFRI's behaved reasonably similar to the first, which was ignited simultaneously with the CRR/GG, and thus it is felt that the initiation of the SPFRI at the beginning of fuel gel expulsion (as has been postulated for the operational model) has been shown to offer excellent promise of successful operation.

3.2.4 Substitution of LP Gas Generator for Solid Grain

As shown in Figure 14, two optional components for the SP F/T were fabricated subsequently to the basic assembly. These components, described in Section 3.1.2 above, were a conical converging front endplate for the fuel tank and an expulsion nozzle with a 0.625-in. exit diameter and burst disc restraint of fuel expulsion. It was desired to evaluate the possible contributions of each of these, individually and jointly, toward minimizing fuel rod dispersion. In addition, high-speed movies were to be made of unignited fuel rods for comparison with the LP F/T expulsion films, the use of a thinner (3% M4 thickener) gel and/or lower pressure were to be explored and certain other ideas were to be investigated if time and funds permitted. An additional important factor to be checked out before final performance firings were made was the operation of the "hydraulic load cell". This was the expedient adopted for measurement of thrust after damage had been sustained by the Statham dynamometer supplied as part of the Flamethrower Research Device. This hydraulic load cell is described in detail below in Section 5.

The number of tests which it was desired to run exceeded the number of solid propellant grains available. In addition, the variations in pressure and in flow rate of pressurizing gas, if at all within the capability of the basic CRR/GG grain as cast, certainly did not admit of precise prediction without some trial-and-error. Since the major fraction of the CRR/GG grain combustion products was vented to the rear to provide only CRR thrust anyway, a simpler method of pressurizing the SP F/T fuel tank for these off-design, exploratory tests was desired. Compensation of recoil in these specific tests was an unnecessary refinement, since thrust presumably could be measured and corrected in subsequent finalized SP F/T firings.

Accordingly, provision was made easily for substitution of the gas generator section of the liquid propellant system (LPGG) described above in Section 2, in place of the SP CRR/GG on the 3-gal. fuel tank. The task of matching propellant flow rate precisely with F/T fuel expulsion rate, to approach a "square-wave" pressure-time history, for varying and unpredictable expulsion rates, was greatly simplified by the provision of a hot-gas throttling relief valve. This simple valve used a light-weight copper plunger which was driven against its seat by an adjustable weight to set the relief pressure; and low force-constant extension springs coupling the weight to the valve stem isolated the plunger from the inertia of the weights to permit very fast valve response to pressure transients. Actual weights were used to load the valve in this fixed-attitude experimental setup, rather than spring-loading, to provide simple adjustment of preload and to avoid the complexity of obtaining and properly supporting compact high-force springs. The valve was installed in a short piece of 2-in. stainless steel pipe which served both to couple the LPGG to the fuel tank, and also as an accumulator to provide initial volume which would afford the relief valve some small amount of time in which to open and attain control of excess gas flow during the initial pressurization transient.

After some preliminary LPGG checkout tests, the liquid propellant feed system was set for each test to provide a fixed, somewhat greater flow rate of combustion gases than was expected to be necessary to match the steady-state rate of expulsion. Thus the system was forced at the beginning of operation to begin dumping overboard a portion of the pressurizing gases, and to continue in this fashion--perhaps with varying rates of gas venting--throughout expulsion. At the end of expulsion, expulsion piston travel (which had been the major gas consumer) ended. This diverted all incoming LPGG products through the relief valve, whose relatively small orifice caused an increase in system pressure above the preset expulsion level, and actuated a pressure switch to shut down the LPGG. This system was found to give quite short pressure rise times (0.05-0.10 sec), steady-state pressure control varying from good to excellent, and reliable shutdown following expulsion.

Much of the effort of this particular phase was devoted to trying to get significant and reproducible thrust calibrations and measurements from the hydraulic load cell system. These problems are discussed more fully below in Section 5. In consequence, some of the less-important items could not be investigated thoroughly in the time available, and the results are perhaps best summarized qualitatively as below.

Test firings of the conical tank end vs. the flat endplate did not show any significant improvement in rod appearance as a result of the conical tank end. In evaluating the 0.625-in. expulsion nozzle with fuel gel, it was found that the home-made burst discs (which had been devised here in order to fit into the existing test hardware and time schedule) did not open fully and clear the fuel rod trajectory, as they had

done in earlier check-out tests with pressurized water. Therefore there was some interference with rod expulsion, with predictably adverse results on rod performance. The motion picture studies of unignited fuel rods from the 0.500-in. expulsion nozzle indicated that the rods from the SP F/T were not smooth and glass-clear, as might have been expected; rather, they were comparable to the best of the rods photographed being expelled from the hose, valve, and gun assembly of the LP F/T. The unignited rods were, in general, continuous and reasonably smooth; there was, however, some small amount of material ejected from the surface in most tests, by some mechanism which is not known with certainty.

The 3%-thickener gels did not appear to produce any less dispersion than did the 4.5%-thickened fuels, and achieved essentially equivalent range; in one ignited test with no wind, the major impact zone stretched from 75 yards to 120 yards, with a 10° firing elevation. The most apparent result of the reduced thickener concentration was a much faster rate of burning in flight; the flame surrounding the first 20 yards of trajectory was noticeably bushier and noisier; and the blobs of gel which impacted downrange were significantly smaller, and burned out more quickly, than those obtained from 4.5%-thickener fuels. Of course, it is possible that the much more fluid 3% gel was more vigorously attacked by the high-intensity SPFRI, and the rod integrity perhaps seriously impaired. However, the attainment of nearly equivalent range by gels of both concentrations under similar conditions suggests that the rods of the two compositions were fairly comparable.

3.2.5 Final Solid Propellant Flamethrower Test Series

The final series of SP F/T tests were intended to provide quantitative data on the recoil and recoil compensation characteristics of this unit as functions of expulsion pressure and nozzle size, together with such pertinent data as expulsion velocity and time, range attained, and the other factors cited above at the beginning of Section 3.2. However, because of the performance of parallel liquid- and solid-propellant programs, and as a result of the operational difficulties discussed in this report, it was necessary to accept some compromises in the quantity and precision of data obtained. The results of this series of six firings are summarized in Table XI and in Figures 18 and 19, and are discussed in the following paragraphs.

The first two firings (FTXS-18 and -19) were made to ascertain what length of CRR/GG grain was required to develop a nominal fuel pressure of 450 psig; earlier tests had developed gel pressures of ca. 400 psia or less. Because of the unpredictable distribution of propellant gas flow between CRR and fuel tank pressurization, the most useful approach was to make duplicate firings with grains of two different lengths. On the first of these, no consistent thrust calibration could be obtained; however, the gel pressure trace (after steady-state was reached) was level and

nearly ideal in magnitude. The second firing produced much higher pressures, and (as may be seen from Figure 18) did not quite reach steady-state expulsion. The amplitude of thrust calibration trace deflections was not large, but appeared to be consistent. However, the 172 lb of CRR thrust at 563 psia was some 58% in excess of theoretical thrust for the given conditions of chamber pressure, throat area, expansion ratio, and propellant expansion coefficient (gamma). Accordingly there is considerable doubt of the validity of this thrust measurement.

In Table XI, it will be noticed that no data on fuel tank volume or expulsion velocity are given for tests FTXS-18 through -20, and those for FTXS-21 are questionable. The reason for this is that when attempting to reload fuel for FTXS-22, it was found that the piston would not return fully to the rear of the tank, with normal loading pressure of 100 psig on the fuel side of the piston. When the rear endplate of the tank was removed, an accumulation of caked and/or frozen (by means of condensed water) NH_4Cl was found which kept the piston approximately 1.88 in. forward of its normal loaded position. This deposit was removed to permit full loading for FTXS-22. It was assumed that this same observed position was attained by the piston when loading fuel for FTXS-21; this was not known with certainty, however. Possible piston position for firings FTXS-18 to -20 were even more uncertain, and thus no fuel volumetric calculations were made. This was justified by a comparison of expulsion times vs. pressures with corresponding data of FTXS-22 and -23, in which piston position after loading was checked (as it had been in earlier firings, preceding FTXS-18).

Firings FTXS-20 and -22 were intended to be duplicate record shots with the 0.500-in. fuel nozzle to provide confirmed performance data at the specified nominal conditions of 0.500-in. nozzle diameter and ca. 12.5 lb/sec flow rate (i.e., approximately 2 gal/sec). The oscillograph firing records are shown in Figure 18. It can be seen for FTXS-20, that thrust oscillations at the beginning of expulsion are reasonably comparable to those of many of the other traces shown, and indicate a reasonable freedom from damping (friction) in the system. Therefore the thrust measurement would seem to be valid, and this is confirmed by reasonably good consistency in calibration values. In FTXS-22, however, the thrust calibrations could not be made consistent, and the firing thrust trace suggests that very considerable damping may have been present. It was not possible to read out any meaningful thrust data from the latter record. However, the very small indicated recoil force imbalance during expulsion is not believed to be valid.

The 0.625-in. fuel expulsion nozzle was tested in Firings FTXS-21 and -23. Since the volumetric expulsion rate through this larger nozzle was expected to be ca. 56% higher than that through the 0.500-in. nozzle (assuming equal exit velocities for equal pressures), a larger CRR/GG grain was used than that used for steady-state nominal 450 psig with the smaller nozzle. However, as may be seen in Figure 19, this larger grain produced

an excessive quantity of gas, and steady-state expulsion was not achieved. Unfortunately, the burst disc also released at 338 psig instead of the intended nominal 400 psig. The marked similarity in pressure levels between FTXS-21 (0.625-in. nozzle) and FTXS-19 (0.500-in. nozzle) suggested that the optimum grain for the smaller nozzle might be nearly adequate for the larger one as well; and to provide direct comparisons, the grain size used for FTXS-20 and -22 was used also with the larger nozzle in FTXS-23. In this latter test, the burst disc released almost exactly at the desired pressure, and a nearly ideal gel pressure-time trace was obtained (although at a lower pressure than desired).

This last firing was made on the last day of the period of technical effort, and thus certain questions had to be left unanswered. However, a very considerable understanding of the behavior of the workhorse SP F/T was gained from this work, and the significant findings are discussed in the following section.

3.2.6 Discussion of Solid Propellant Flamethrower Results

First, it must be emphasized that the very large forward thrusts observed for the workhorse SP F/T between the end of expulsion and grain burnout will not be encountered in an operational model. Partly this will be so because the operational SP F/T will be designed to achieve grain burnout either at, or probably shortly before, end of expulsion; whereas in the workhorse model, the grain was not tailored exactly to expulsion time, but rather was intended to burn at least for full expulsion to ensure steady-state operation. This alone, however, would not eliminate a terminal forward thrust, because at end of expulsion the fuel tank (3 gal capacity) would be pressurized to ca. 450 psig. and the relatively long exhausting of this large quantity of gas through the CRR nozzle would generate an uncontrollable forward impulse. The prime reason that thrust imbalance will not occur is, as was described above at the beginning of Section 3.2, the plastic cup-piston will be provided with a weak blow-out port which will fail at ca. 30-50 psi differential pressure. The differential pressure across this cup-piston during pressurization transient and expulsion will be very small, much less than that across the heavy, seal-equipped piston of the workhorse SP F/T, because of the low friction between sliding plastic surfaces and the absence of high-friction piston seal cups. However, when the cup-piston reaches the front of the operational SP F/T fuel tank essentially all fuel will have been expelled. Flow through the fuel nozzle--which had been the only factor generating backpressure in the fuel--will cease, and pressure ahead of the piston will drop. As soon as the pressure differential exceeds the strength of the piston blow-out port, this port will rupture. Then the stored high-pressure gas can vent to the front as well as to the rear; and appropriate balancing of CRR and expulsion nozzle diameters can provide nearly complete thrust compensation in opposite directions.

Next it is important to consider the shape of the thrust-time curves (even if the magnitudes may be somewhat uncertain). Those of FTXS-19 (Figure 18) and -21 (Figure 19) appropriately may be disregarded, since

steady-state conditions were not attained simply because of controllable parameters. An examination of FTXS-20 and -22 show that an initial imbalance was attained, followed by a gradual increase in imbalance, followed by a final period of nearly constant thrust. The imbalance at any one point could easily be corrected by adjustment of propellant grain and nozzle dimensions; however, this would still produce imbalances, perhaps in opposite directions (extremely undesirable), at other times during expulsion. It also is conceivable to design a grain with a pre-programed thrust variation that would closely approximate a well-characterized expulsion thrust-time curve. However, FTXS-23 shows a thrust-time trace which is very nearly constant throughout expulsion; this would be eminently simpler to compensate closely. Why is there a difference, and is it significant?

The difference, and it has considerable import, lies in the gel pressure-time (and hence expulsion rate-time) relationship. Because of the burst disc operation in FTXS-23, the gel pressure-time trace is very nearly constant (100% of expulsion at 95±5% of peak gel pressure; and even this behavior can be refined with moderate effort). Thus the recoil force-time curve legitimately can be expected to be very nearly constant. And this type of operation is precisely that which should afford the most uniform range (once fuel rod stability is obtained via adjustment of expulsion nozzle and gel characteristics, which was not a part of this contract). As has been pointed out earlier, the burst disc function would be provided in an operational SP F/T by the plunger in the expulsion nozzle which serves to initiate the SPFRI at the beginning of fuel expulsion. Therefore it is entirely reasonable to expect that a thrust-time curve of the type obtained in FTXS-23, and which is easily compensated for by proper selection of grain and nozzle dimensions, can be attained in an operational SP F/T.

The relatively large-amplitude transient thrust oscillations in both directions (well beyond steady-state values) might seem to be cause for alarm. However, it must be realized that the amplitude and duration of these oscillations are intimately associated with the mass, spring constant, and damping factor of the particular system, as well as the forcing function itself. An operational SP F/T would have less than 40% of the mass of the workhorse unit, hence would store equivalently less oscillatory energy. The "spring constant" of the operator would be several orders of magnitude lower than that of the thrust measuring system, and the damping would be considerably higher; thus the frequency and duration of oscillation would be reduced, and probably only a simple small displacement without oscillation would occur. Finally, because of better thrust compensation, the forcing function (which excites the oscillation to begin with) would be much smaller, hence would create less initial disturbance.

In many of the firing records, CRR chamber pressure began to rise before expulsion occurred. This was due, in Figure 18, to some initial sticking of the piston, until the break-away force was reached; and in Figure 19, to fuel restraint until release of the burst disc. This phenomenon, which probably also will be encountered in an operational unit, imparts a

small forward impulse to the F/T. While in a rigid thrust mount, the F/T is restrained and the forward force is measured; however, when held in the relatively "soft" restraint afforded by hand-held operation, this impulse would be transformed, at least to some extent, into forward velocity. Almost immediately, however (in an operational SP F/T), the blowing-off of the weather cap on the SPFRI would produce an opposing impulse which easily can be tailored to compensate for the earlier forward increment. The question is, what happens to the F/T, the operator, and the initial alignment of aim during all this disturbance? Since these disturbances occur at the moment of firing, the entire mass of the loaded SP F/T is available to absorb the impulse. Thus the accelerations are only of the order of 1-3 g; the period of the forward impulse is only 0.05-0.08 sec, and this may be reduced in an operational model; thus the displacement, if totally unrestrained, is a fraction of an inch, and much smaller with even moderate restraint (as one would normally exert in supporting a 30-lb weight); and all accelerations are directly coaxial with the centerline of the F/T. Thus it is believed that these transient phenomena will cause essentially no disturbance of aim, nor problems of operator control or balance.

Thiokol
REACTION MOTORS DIVISION

TABLE XI

SOLID PROPELLANT-ACTUATED, RECOIL-COMPENSATED LONG-RANGE FLAMETHR'WER TEST FIRINGS

	Firing Number FTXS- 11	12	13	14	16	17	18	19	20	21	22	23
Overall Grain Length, in.	6.405	6.440	6.400	6.410	6.400	6.400	7.040	7.682	7.040	7.670	7.040	7.040
Slot Length, in.	2.010	2.000	2.032	2.032	2.025	2.025	2.291	2.525	2.265	2.535	2.270	2.265
Propellant Weight, lb.	0.844	0.849	0.848	0.850	0.850	0.845	0.930	1.020	0.924	1.011	0.926	0.930
Booster Grain Thickness, in.	--	--	0.113	0.195	0.305	0.313	--	--	--	--	--	--
Booster Grain Weight, lb.	--	--	0.013	0.023	0.035	0.036	--	--	--	--	--	--
CRR Nozzle Throat Dia., in.	.402	.402	.403	.403	.405	.406	.407	.407	.408	.408	.409	.410
CRR Nozzle Exit Dia., in.	1.183	1.183	1.183	1.183	1.183	1.183	1.183	1.183	1.183	1.183	1.183	1.183
Fuel Expulsion Nozzle Dia. in.	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.625	0.500	0.625
Fuel Rod Igniter Used	Chrom. Nit. (Missed Rod)	Chrom.Nit.	SP-6"	SP-3"	SP-3"	SP-3"	SP-2"	SP-2"	SP-2"	SP-2"	SP-2"	SP-2"
Peak Chamber Pressure, psig	--	--	--	424	N O		499	549	472	534	463	390
Peak Tank Gas Pressure, psig	392	380	427	418	D A T A		495	538	465	502	453	368
Peak Gel Pressure, psig	380	368	412	374			469	522	453	510	437	348
Gel Pressure @ Disc Release, psig	--	--	--	--	--	--	--	--	--	338	--	398
Peak Steady-state Net Thrust, lb.	Excessive	Oscillation	--	--	--	--	--	58 R 172	64 R 72	148 R 84	-- --	91 R 61
Total Expulsion Recoil, lb.	Excessive	Oscillation	--	--	--	--	--	230	136	232	--	152
Rocket Thrust at End of Expulsion, lb.												
Total Expulsion Time, sec	1.656	1.600	1.13	1.450	1.35	1.335	1.050	1.252	1.237	0.620	1.350	0.894
% T.E.T. @ 95% ±5% P_{Max}	--	--	--	83	--	--	61	51	66	59	77	100
Fuel Volume, Gal (Calc.)	3.23	3.23	3.23	3.23	3.23	3.23	?	?	?	~2.81	3.22	3.22
Avg. Expulsion Velocity, Ft/Sec	192	198	280	219	235	238	?	?	?	~284	234	226
Avg. Gel Pressure, psig	--	--	--	--	--	--	368	428	392	469	389	344
Max. Range/Min. Range, Yd.	65/10 unign.	120/50	127/89	160/68	149/93	145/77	105/55	138/86	130/62	108/74	142/90	105/53
Est. Center of Deposit, Yd.	--	85	100	127 & 83	112	105	80	110	100	90	115	80
Lateral Dispersion, Yd.	±1	±1	±3	±3	±4	±3	±2	±3	±3	±3	±2	±3
Wind Speed/Bearing, MPH/Degrees	0/	0/	3-5/ 200 290	0/	0/	0/	0/	0/	0-2/ 320	0/	0/	0/
Firing Elevation, Degrees	15	15	15	15	15	15	10	10	10	10	10	10
Nature of P-T Curve			Level (Slow Rise)	Sl. Hump	Sl. Hump	Sl. Hump	Level	Slowly Rising Bumpy	Level	Rising	Level	Level
Thrust Mount Support	MG Tripod	MG Tripod	Pedestal	→	→	→	→	→	→	→	→	→
			Load Cell Damaged	No Thrust Measurement								

4.0 GEL ROD CHARACTERISTICS

Although investigation and optimization of gel rod characteristics were not within the scope of this program, studies of these associated phenomena are pertinent to the ultimate development of an operational long-range portable flamethrower since range and weapon effectiveness are a very definite function of rod quality. Attempts were made to determine the degree to which system components affected gel rod characteristics although the scope of this study was necessarily limited by the overall objectives of this program. Some of these observations are discussed below.

The gasoline gel used in this study can be described as simultaneously thixotropic, viscous, elastic, and incompressible. The thixotropic properties are derived from a characteristic structure which exhibits a gel strength while at rest which differs from its strength when being deformed. Thixotropic properties are dependent on the deformation rate as well as the formation or healing rate, and on the elastic nature of the gel. The manner in which this gel flows is known as plastic flow because the viscosity decreases as the shearing stress increases.

High speed photography was used in many gel expulsion experiments with the result that extremely interesting phenomena were brought to light which might otherwise have been overlooked. Various gel rods were photographed emerging from the solid propellant system, and from the liquid propellant system, both unignited and ignited.

Some tests with the liquid propellant system which consisted of more than one burst per tankful of gel had distinctly different gel rod characteristics for each burst. In one run (FTXL 4, Table VII) the second burst had a more uniform gel rod, produced greater thrust and had a longer range with less dispersion or ground scatter than did the first burst. The interval between first and second expulsions was on the order of several minutes. The system pressure during this period decayed to about 100 psi due to cooling of the hot gases. During this test, cameras were focused on the first two feet of gel rod after emergence from the nozzle. The first burst had a sheath or boundary layer surrounding the rod which rapidly diverged when issuing from the nozzle while the second burst appeared to have a smooth uniform surface with no divergence apparent.

The best gel rod appearance obtained with the liquid system was during a test in which the gel pressure decayed from 450 psi to atmospheric upon opening of the gel valve (FTXL 7). The exit velocity was reduced from almost 200 fps at the beginning of flow to zero when the rod was broken. The elastic properties of the gel are evident in axial rod oscillations since the rapid change in exit velocity undoubtedly caused stretching of the rod. There was almost no divergence or tearing and the rod appeared more homogeneous than any other obtained.

In contrast with this test, most other liquid propellant system tests showed discontinuities, rod break-up very soon after emergence from the nozzle and differences between tests in the degree of uniformity in the gel rod. In spite of the irregularities, a maximum range greater than 120 yards has been obtained, although considerable longitudinal scatter has been evident.

Some of the significant conditions affecting gel rod integrity in either the solid or liquid propellant systems are

1) The rigidity of the thrust mounts,
2) Entrained air or vapor in the gel,
3) Unknown storability characteristics of the gel,
4) The effects of the flow passages on the gel,
5) Ignition systems,
6) Visco-elastic flow characteristics of the thickened fuel.

For the SP F/T, the thrust mount was installed on an extremely rigid pedestal outside the turret (except for the first ignited firing). For the LP F/T, the mount was installed on the machine gun tripod of the Flamethrower Research Device. Thrust measurements showed clearly that this tripod is an extremely non-rigid support with a low spring constant. Thus, it is possible that the LP F/T tests made from the tripod suffered from the imposition of small initial disturbances (in any plane) of the gel rod by deflection of the supporting tripod. These initial disturbances then could be amplified by aerodynamic forces, as has been shown in theoretical analyses of fuel rod aerodynamics.

In initial tests with the liquid propellant system when ignition was not attempted, blobs of gel lying on the ground after flight contained numerous small bubbles indicating the entrainment of gas. This gas probably was air entrapped during the filling process, although the fill line was primed before reloading the tank and residual gel in the tank should have precluded the introduction of air. A bleed was installed on the tank to vent air while loading the gel tank, and subsequent tests showed that blobs of gel found on the ground contained very few bubbles. An improvement in rod characteristics was similarly noted in the several shots made after the air bleed was installed. The SP F/T had an air bleed for tank venting when gel is being loaded, thus air entrainment has never been considered a problem with this system, but may account somewhat for the relatively good performance compared to early liquid propellant system firings.

Batches of gel (which were government furnished) were mixed at two different times and stored for periods varying from one week to 4-1/2 months before use. Since this portion of the program was limited, no conclusive correlations were obtained between gel storage conditions and favorable gel rod characteristics although initial tests with a fresh batch appeared to be better.

The liquid propellant system has been described previously and is shown in Figure 2. It can be seen that the gel must travel from an eight-inch diameter section, through a 1.3 inch ID flexible hose, through several discontinuities including pipe connections, a valve and a nozzle. In contrast, the SP F/T gel must pass only from the eight-inch diameter tank, through a short connecting section to the nozzle. It would appear that the latter configuration is better from the flow path standpoint. Since the healing time of this particular gel is rather long (perhaps 20 minutes), the fewer discontinuities and irregularities that the gel is subjected to would appear to provide the best conditions because healing obviously could not occur in the nozzle.

High speed films of the fuel rod just after leaving the nozzle indicated that gel rod ignition by chromyl nitrate was not always continuous. This may have resulted from dropwise impingement and/or occasional failure to impinge. It is possible that this could cause a pulsating disturbance upon the fuel rod because ignition with chromyl nitrate seems to be a relatively violent reaction. In any case, the disturbances were not axi-symmetric, since impingement occurred only from one side of the rod and probably also varied somewhat in angular orientation about the axis of the fuel rod. In contrast to this, the SPFRI completely surrounded the fuel rod with a concurrent axi-symmetric flow of hot gases and Al_2O_3 particles. Instead of a spontaneous reaction between condensed phases occurring at the fuel rod surface, vaporization of the fuel probably occurred with subsequent ignition at some distance from the rod surface. Thus, the LP F/T may have suffered from a more disturbing type of rod ignition.

From photographs of several SP F/T firings, the gel rod was apparently smooth and homogeneous to a distance of four feet from the nozzle. Disturbances and discontinuities were evident at this point and tended to grow as the distance from the nozzle increased. In general, the characteristics of the rods produced by the SP F/T were of the same nature as those of the best rods produced by the LP F/T under steady-state conditions. Similarly, the ranges obtained with SP F/T firings exceeded LP F/T firings in most cases, with a maximum SP F/T range of 160 yards obtained.

Thus, many factors can be described which may affect the formation of the gel rod, may reduce or exaggerate disturbances in the rod during or after expulsion, and hence may lead toward or away from maximum effectiveness and minimum dispersion. After reviewing some of the flamethrower firings and high-speed movies of unignited fuel rods, Mr. W. Beyth (Contract Project Officer on this program) arranged for a consultation between Thiokol personnel involved in this effort, himself, and Dr. W. Philippoff of Esso Research and Engineering Company (Dr. Philippoff formerly was associated with Franklin Institute, where he conducted intensive investigations of flamethrower fuel gels over a period of years). The erratic behavior of rods observed in this program were described, and some of the high-speed films were shown. Dr. Philippoff then was asked for his opinions as to the possible sources of the observed undesirable phenomena, and for any recommendations toward possible improvement.

Dr. Philippoff stated that he felt that the fault probably did not lie with the techniques of pressurization, but rather principally in the high concentration of thickener, and in the use of M4 thickener rather than M1 (although it was recognized that M1-thickened fuels were subject to much more severe degradation upon aging than M4-thickened gels). Of course, the 4.5% nominal thickener content chosen for this program was based upon a series of tests of range vs. pressure and thickener content which had been made earlier at Edgewood Arsenal. He observed, also, that the more non-Newtonian the fluid, the more unpredictable became its behavior; that there is little or no effective, quantitative knowledge of the effects of flow channel constriction upon rod characteristics, except perhaps that any constriction is bad, and perhaps the greater the degree, the worse the result; that the phenomena governing rod stability and length are essentially unknown. He suggested that rod improvement might be obtained by reducing thickener concentration, by decreasing expulsion pressure, or by reducing the viscosity of the 4.5%-thickener gel by addition of cresol. He reiterated, however, that there was no assurance that any of these would help; at the present state-of-the-art, all one could do was try each and observe.

Subsequently, the first two of these suggestions were evaluated, at least briefly. A special drum of 3%-thickened fuel was prepared promptly by CRDL and shipped to RMD. Two ignited firings of this gel showed substantially the same degree of dispersion and non-reproducibility found with the original thicker gel. In addition, much more of the gel appeared to burn up in flight, which was undesirable. Firings of 4.5% gels through the 0.500-in. fuel nozzle at gel pressures from 368 to 522 psig did not produce any significant or consistent change in the degree of dispersion; and at 348 psig through the 0.625-in. nozzle, shorter range but equivalent longitudinal dispersion was obtained.

The results of these limited tests appeared to substantiate Dr. Philippoff's observations concerning the largely-empirical approach required in attempting to improve gel rod behavior. Since gel rod problems were not properly a major part of the effort under this contract, it was not possible to pursue the matter any further at this time.

5.0 THRUST MEASUREMENTS

Thrust measurements were made in this program with several combinations of force measuring devices and flamethrower thrust mounts. The liquid propellant-actuated flamethrower utilized the tripod-supported thrust mount shown in Figure 20 (and a different view in Figure 10) for all tests, while the solid propellant-actuated flamethrower used a new flexure thrust mount shown in Figure 15, supported either by the tripod or by the rigid mount embedded in concrete shown in Figure 15 and 23. A Statham Laboratories dynamometer Model No. D4-200TC-350 with 200-lb capacity in either tension or compression provided with the tripod mount as part of the government-furnished Flamethrower Research Device was used until it was damaged (as described below).

When the Statham load cell was damaged, it was found that delivery of a replacement unit could not be made in time to permit performance of tests required for this program. Therefore an alternate means of thrust measurement was needed promptly. Since both thrust mounts had been designed around the very compact Statham transducer, there was not enough space available to accommodate the Baldwin or Alinco load cells generally used at RMD. After consideration of several alternatives, it was decided to use a small double-acting hydraulic cylinder to convert forces into hydraulic pressures which could then be measured by available pressure transducers. An analytical evaluation of this approach is presented later in this section.

5.1 Liquid Propellant-Actuated System

As shown in Figure 10, the gel supply tank for the liquid system was connected to the gun and nozzle by a ten-foot section of flexible hose. The flame gun was supported on the "roller thrust mount" by two bottom rollers, one top roller, and three pairs of side rollers which constrained all motion except in the axial direction. The load cell had one end fixed to the tripod base and the other to the movable gun carriage. A load of 100 pounds corresponded to a calculated movement of about .003 inches.

Attempts to obtain free movement of the gun in its mount without introducing excessive looseness and rattling were largely unsuccessful. With a relatively tight fit, recorded traces made during the application and removal of calibrated weights showed large zero shifts depending on the direction of applied load. When the carriage restraints were loosened to permit friction-free movement, excessive oscillation of the load cell (and hence in the recorded traces) resulted. It was determined that the natural or resonant frequency of the load cell coupled to the F/T assembly was ca. 100 cps. The oscillations measured with the freely moving mount showed a frequency of 9 to 12 cps and were attributed to flexing of the mounting

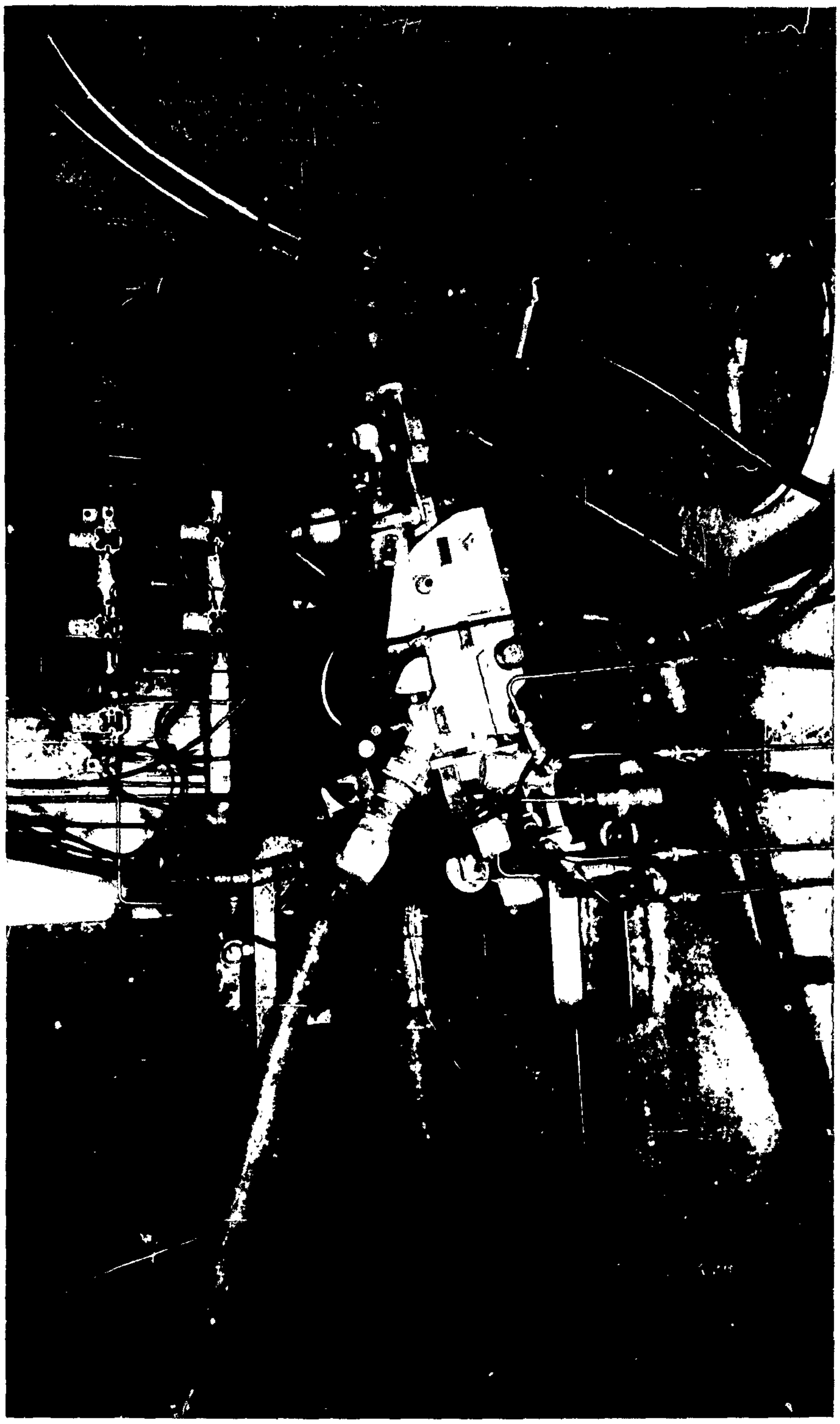


Figure 20. Liquid Propellant-Actuated Recoil Compensated Flamethrower Gun on Roller Thrust Mount

system. Structural bending during gel expulsions could be somewhat removed (and therefore recorded trace oscillations reduced) by pre-loading the mount and load cell. No consistently satisfactory adjustment of the gun carriage was achieved although reliable measurements were obtained with considerable and constant expenditure of effort.

It was determined through several separate tests that many factors affected the thrust trace of the Flamethrower Research Device, particularly in transient periods. Some of these were:

A. Pressurization by gas generator with expulsion valve closed
   1. Internal gel movement to fill up voids,
   2. Hose flexing (Bourdon tube effect),
   3. Movement of 10 gallon gel tank due to 1 and 2, coupled to gun through hose,

B. Expulsion transient periods (startup and shutdown)
   1. Reaction due to gel valve operation,
   2. Ten gallon gel tank movement due to pressure difference between gas generator chamber and gel outlet,
   3. Unsteady dynamic forces of gel on hose due to varying flow rate and frictional effects of gel in hose.

While most of these items did not repeat consistently, some transient thrust peaks of 70-80 pound magnitude were obtained due to gas generator pressurization with no gel expulsion.

During steady-state portions of the runs most of these factors were not present, and if consistent zero references were obtained before and after the test, fairly reliable thrust measurements could be obtained.

5.2 Solid Propellant-Actuated System

Initial solid propellant grains were fired for characterization of rocket parameters in a test stand with existing thrust measuring equipment. The thrust mount consisted of a heavy plate supported on double sets of bearings arranged in a parallelogram to permit small plate movements and thrust measurements parallel to the base.

For the complete SP F/T system tests, it was necessary to fabricate a new thrust mount, since the SP F/T could not be supported in the roller thrust mount of the Flamethrower Research Device. This flexure thrust mount was designed to permit installation on the tripod of the Research Device, and to use the same Statham load cell as was furnished with the roller thrust mount. Flexure plates were utilized to permit friction-free thrust recording. Here again, thrust measurements suffered from tripod deficiencies and attempts at bracing, including attachment to the floor by means of a turnbuckle (see Figure 10), were not completely satisfactory. Preloading the load cell (and the entire mounting system) effectively reduced the recorded oscillations and made transient recordings easier to interpret. This preloading was accomplished by leaving some of the calibration weights attached to the thrust mount during the firing, and thereby establishing a new

"zero-thrust" reference position of the trace.

The Statham load cell, which could measure applied forces either in tension or compression, apparently had an extremely non-linear element by which loads were converted to electrical signals. At its mid-point or no-load position, very small applied loads or disturbances caused relatively large deflections on recording equipment while incremental loads at the 100-pound level produced relatively small additional deflections. Therefore, when the solid propellant-actuated system was moved to the rigid I-beam base shown in Figures 15 and 23, the pre-load was still used because of the load cell characteristics. An excessive transient recoil force apparently was developed upon ignition of the SPFRI in test FTXS-13 (as described above in Section 3.2.3), and the tension-sensing element of the transducer was damaged.

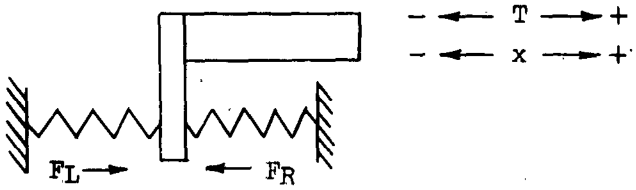
5.3 Analytical Investigation of a Hydraulic Load Cell

When it became necessary to find a substitute means of measuring thrust in either tension or compression, one of the possibilities considered was the use of a double-acting hydraulic cylinder to transform force into hydraulic pressure, which could be measured with available pressure transducers. A brief analytical investigation of this concept indicated that it offered some very attractive features, especially in lower force ranges of the magnitudes anticipated in this program. The analysis is presented below, both to show the reasons for selection of the hydraulic load cell for this program and for whatever general application it may have in other low-thrust measurement applications.

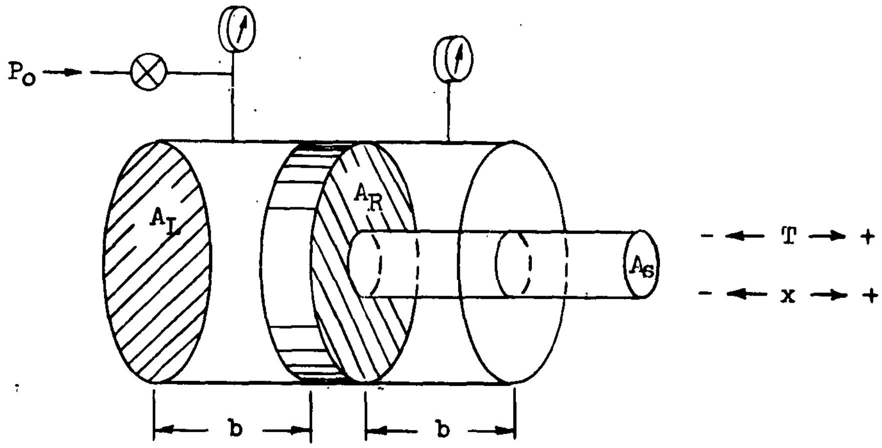
The premise here is that the hydraulic cylinder is completely filled with a liquid hydraulic fluid, free of any gas or vapor bubbles. The liquid is under some initial pressure P_o, and is trapped between valves so that the mass of fluid on either side of the piston is constant; the liquid is not incompressible, however. All piston and rod seals are assumed to be leakproof and friction-free. The cylinder is assumed to be completely rigid (i.e., does not expand with pressure), and inertial forces are neglected.

Most double-acting hydraulic cylinders (except those with piston rods emerging from both ends of the cylinder, which would be undesirable for this application) present different amounts of piston area to the hydraulic fluid on opposite sides of the piston. This results from the loss of piston exposure on the rod side by that portion of the piston covered by the piston rod or shaft (A_s), as shown in Figure 21 b. Before proceeding to the analysis of this situation, however, consider first the simpler condition of a cylinder with equal area on both sides of the piston (e.g., if $A_s = 0$ in Figure 21 b), and the mechanical analog thereof shown in Figure 21 a.

Since the hydraulic fluid is assumed to be compressible (as all liquids in fact are), the equal-area cylinder with elastically compressible fluid on



a) Mechanical analog of equal area cylinder



b) Unequal area hydraulic cylinder

Figure 21. Hydraulic Load Cell Schematic Diagrams

both sides of the piston is directly equivalent to the mechanical analog of Figure 21 a, in which the springs are assumed to have equal, linear force constants (force constant = rate of change of force with deflection). Note that this assumes equal volumes of hydraulic fluid on both sides of the piston, thus equal lengths of fluid column. The two springs are assumed to be equally precompressed to exert a force F_o with no load T applied to the system. Then

$$\Sigma F = F_L + F_R + T = 0 \qquad (1)$$

When $T = 0$, $x = 0$, $F_R = -F_L = -F_o$

For any linear spring, $F = -kx$

Therefore, for any condition of T (and hence, of corresponding displacement x),

$$\left.\begin{aligned} F_L &= F_o - kx \\ F_R &= -F_o - kx = -(F_o + kx) \end{aligned}\right\} \qquad (2)$$

From (1) and (2), $T = -F_L - F_R$

$$T = -F_o + kx + F_o + kx$$

$$T = 2\,kx \qquad (3)$$

For hydraulic fluids, let ϕ be defined as the rate of change of pressure with per cent change in volume; i.e.

$$\phi = \frac{-\,P}{\Delta V/V} \qquad (4)$$

This quantity is not linear over pressure excursions of ca. 10,000 psi, but is very nearly linear over perhaps 2000 psi, especially in the range 0-3000 psia. It is assumed linear here. Considering Figure 21 b with $A_S = 0$,

$$\frac{\Delta V}{V} = \frac{x\,A_L}{b\,A_L} = \frac{x}{b} \qquad (5)$$

and $$P = \phi\,\frac{\Delta V}{V} = \phi\,\frac{x}{b} \qquad (6)$$

Therefore
$$\left.\begin{aligned} F_L &= (P_o - \phi\,\frac{x}{b})A_L \\ F_R &= (-P_o - \frac{\phi x}{b})A_L = -(P_o + \frac{\phi x}{b})A_L \end{aligned}\right\} \qquad (7)$$

Now consider the unequal-area cylinder case, as actually shown in Figure 21 b.

$$\left.\begin{aligned} F_L &= P_o A_L - \phi \frac{x}{b} A_L \\ F_R &= -\left(\frac{A_L}{A_R} P_o A_R + \phi \frac{x}{b} A_R \right) = -\left(A_L P_o + \phi \frac{x}{b} A_R \right) \end{aligned} \right) \quad (9)$$

From (1) and (9), $T = \phi \frac{x}{b} (A_L + A_R)$ (10)

Transposing (10), $x = \frac{b \quad T}{\phi \; (A_L + A_R)}$ (11)

Equation (11) permits calculation of the piston displacement which will result from a given combination of cylinder, fluid, and load. It is important to note that this displacement for a given load is independent of initial pressure; and another transposition of (10) yields the spring constant of the hydraulic load cell,

$$k = -\frac{T}{x} = \frac{\phi}{b}(A_L + A_R) \quad (12)$$

The importance of this will be discussed later.

Equation (10) itself is of no value for calculating the thrust applied to the load cell, because the displacement x is not known (and later will be shown to be very small). The intent was to use pressure as a measure of thrust. From Equations (9) and (11),

$$F_L = P_o A_L - \frac{\phi}{b} A_L x = P_o A_L - \frac{\phi}{b} A_L \frac{b}{\phi} \frac{T}{(A_L + A_R)}$$

$$F_L = A_L \left[P_o - \frac{T}{(A_L + A_R)} \right] \quad (13)$$

At all times, if F_L is the total force on A_L,

$$P_L = \frac{F_L}{A_L} = \frac{1}{A_L} A_L \left[P_o - \frac{T}{(A_L + A_R)} \right]$$

$$P_L = P_o - \frac{T}{(A_L + A_R)} \quad (14)$$

For the right face of the piston, because of the directional sign convention,

$$F_R = - P_R A_R$$

From (1)

$$\Sigma F = F_L + F_R + T = P_L A_L - P_R A_R + T = 0$$

$$P_R = \frac{P_L A_L + T}{A_R} \tag{15}$$

From (14) and (15),

$$P_R = \left[P_o A_L - \frac{A_L \quad T}{(A_L + A_R)} + T \right] \frac{1}{A_R}$$

Factoring out A_L,

$$P_R = \frac{A_L}{A_R} \left[P_o - T \left\{ \frac{1}{(A_L + A_R)} - \frac{1}{A_L} \right\} \right] = \frac{A_L}{A_R} \left[P_o + T \left\{ \frac{A_L + A_R}{A_L(A_L + A_R)} - \frac{A_L}{A_L(A_L + A_R)} \right\} \right]$$

$$P_R = \frac{A_L}{A_R} \left[P_o + \frac{T \quad A_R}{A_L(A_L + A_R)} \right] \tag{16}$$

Thus the thrust can be obtained in terms of known and measurable quantities, including either P_L or P_R at the option of the experimenter: transposing (16),

$$T = (A_L + A_R)(P_R - \frac{A_L}{A_R} P_o) \tag{17}$$

Alternatively, (14) yields

$$T = (A_L + A_R)(P_o - P_L) \tag{18}$$

The magnitude of pressure variation, ΔP, for a given T can be found from (14) and (16) for the left and right sides, respectively. From (14),

$$|\Delta P_L| = P_o - P_L = \frac{T}{(A_L + A_R)} \tag{19}$$

From (16),

$$|\Delta P_R| = P_R - \frac{A_L}{A_R} P_o = \frac{T}{(A_L + A_R)} \tag{20}$$

Thus, as might be expected, the magnitudes of pressure fluctuations on opposite sides of the unequal-area piston are equal and linear--provided that both P_L and P_R are at all times greater than zero.

It was found, however, that the O-ring piston seal was able to move independently of the piston (over small displacements) because of conventional clearance in the O-ring groove. This happened when the direction of the pressure gradient across the O-ring changed upon application of sufficient compression to make P_L exceed P_R, and produced anomalous thrust recordings. Therefore it was desired to determine what minimum preload pressure P_o' (on the left side of the piston) would be required for a given T to prevent change of direction of pressure gradient; i.e., in the limit, for the given T, what P_o' will make $P_R - P_L = 0$, or $P_R = P_L$? From (16) and (14),

$$P_R - P_L = \frac{A_L}{A_R} P_o' + \frac{T}{(A_L + A_R)} - P_o' + \frac{T}{(A_L + A_R)} = 0$$

$$P_o' \left(\frac{A_L}{A_R} - 1\right) + \frac{2\,T}{(A_L + A_R)} = 0$$

$$P_o' = \frac{-2\,T}{(A_L + A_R)} \cdot \frac{A_R}{(A_L - A_R)}$$

Thus, $$P_o' = \frac{-2\,T\ A_R}{A_L^2 - A_R^2} \qquad (21)$$

The outstanding advantage of a hydraulic load cell for low-force applications results from its superior stiffness (or high force constant, k) in comparison with conventional strain gage load cells designed to measure low thrusts. This stiffness increases the natural frequency of the spring-mass system, reduces the amplitude and stored energy of the system vibrations, and hence favors rapid decay of oscillations to the actual applied load condition. The natural frequency of a one-dimensional vibrating spring-mass system is given by

$$f_n = C\sqrt{\frac{k}{m}} \qquad (22)$$

where C is a constant dependent on the units used and m is the vibrating mass. Therefore the greater the k, the higher the natural frequency--which for thrust measurement purposes is highly desirable.

This advantage can best be shown by a numerical example which is pertinent to this program. As noted earlier, the Statham dynamometer had a calculated deflection of ca. 0.003 in. for a 100-lb load. By definition as shown in 12,

$$k_s = -\frac{T}{x} = -\frac{100}{-.003}$$

$$k_s = .33 \times 10^5 \text{ lb/in.} \qquad (23)$$

The ϕ for hydraulic fluid was assumed equal to that for mineral oil, for which compressibility data were available. Mineral oil was found to compress nearly linearly by 2% from 0 to 5000 psi pressure. From (4),

$$\phi = \frac{P}{\Delta V/V} = \frac{-5000 \text{ psi}}{-.02} = 2.5 \times 10^5 \text{ psi}$$

The hydraulic cylinder used had a bore of 0.625 in., piston rod of 0.3125 in., and the piston was positioned at midpoint of the 1.50-in. stroke (i.e., b = 0.75 in.). Then from (12),

$$k_c = \frac{\phi}{b}(A_L + A_R) = \frac{(2.5 \times 10^5)(.3065 + .230)}{.75}$$

$$k_c = 1.79 \times 10^5 \text{ lb/in.} \qquad (24)$$

Thus the cylinder had a k approximately 5.5 times that of the Statham. Furthermore, it would have been a simple matter to increase the k of the cylinder to 50 times that of the Statham by placing inserts inside both ends of the cylinder to limit the length of the oil column, b, to ca. 0.075 in. instead of 0.75 in.

The k of most load cells continues to decrease linearly with maximum thrust capability because the deflection required for normal signal output (i.e., the distortion of the strain gage) must be maintained essentially constant in the range 0.003-0.006 in., while the force by which this deflection is divided decreases with transducer thrust rating. In experimental systems where the device generating the small force has a significant weight (mass), very large and long-sustained oscillations can result which may completely mask the event which is to be studied. It would seem that hydraulic load cells, with the very high k's which can be obtained, should be of considerable help provided they are carefully designed.

Unfortunately for this program, the direct utilization of a commercial hydraulic cylinder did not afford several of the ideal qualities assumed above. The mobility of the piston seal (O-ring) with respect to the piston has already been discussed. Both this seal and the seal between piston rod and cylinder head were not devoid of friction; when moved by hand in the lubricated but unpressurized condition, breakout force was estimated at 5-10 lb, and not necessarily repeatable. The breakout force when pressurized was not known. It had been assumed that in operation as a load cell, breakout force would not enter the picture because expected deflections of under 0.001 in. would fall well within the elastic deformation of the O-ring without requiring relative motion between O-ring and cylinder. This assumption may have been appropriate for the O-ring seal on the piston; however, the piston rod seal was a packed joint rather than an O-ring, and hence probably did not exhibit equivalent resiliency. This condition probably also was exaggerated by hydraulic pressurization to between 1000 and 2000 psi during operation.

Some small leakage was observed occasionally during thrust calibration. It is believed that this leakage occurred through the hand valves used to isolate the fluid filling the cylinder from the reservoirs provided at both ends of the cylinder to permit small adjustment of piston position.

There also appeared to be difficulty at times in completely eliminating entrapped air. This was due in part to the internal configuration of the cylinder and in part to the associated fill-and-vent and pressure transducer attachment fittings.

For all of the above reasons, and because of frequently observed non-linearities (due to whatever cause) during thrust calibration by direct attachment of known weights up to 100 lb in either recoil or counterrecoil direction, the actual system pressure was not used as a measure of thrust. Rather, a given preload pressure was applied to the system, and then the calibration weights were attached and removed incrementally in both directions, with thrust trace (hydraulic pressure) recordings being made at each step. The actual trace deflections for known loads then were used to calculate a scale factor in lb/in. of deflection, irrespective of system pressure.

The overall result of the loss of the Statham dynamometer and of the substitution of the hydraulic load cell, coupled with some instrumentation difficulties, was that thrust measurements were not completely satisfactory. The apparent non-linearities of the particular Statham load cell provided as part of the government-furnished Flamethrower Research Device gave rise to considerable doubt that well-defined thrust data could have been obtained even if that transducer had been used throughout the program; however, this cannot be stated with certainty.

6.0 FLAME WEAPONS TEST RANGE

All firings of both solid and liquid propellant-actuated flamethrowers with fuel gels were conducted at the RMD Flame Weapons Test Range. This range is located at the RMD Secondary Waste Disposal Area, adjacent to Lake Denmark Road and the RMD Test Area R-S, and to the northeastern end of the Picatinny Arsenal reservation, in Telemark, N. J. This range (see Figure 22) has a cleared area with maximum length and width of approximately 200 yd and 80 yd, respectively. The flamethrower firing site is located approximately 15 yd in from the south end of the range (bottom of Figure 22), with the firing direction lying about 30° east of (magnetic) north. The ground is level within ±3 ft along the first 150 yd of the impact zone, drops abruptly about 5 ft, and is then roughly level to the edge of the woods at about 180 yd range. A wind speed and direction sensing unit is positioned about 12 ft above ground at the steel turret visible near mid-range, approximately 60 yd from the firing site; thus it is positioned close to the midpoint of expected trajectory, both horizontally and vertically.

Figure 23 shows a view of the flamethrower firing site, looking from downrange directly down the muzzle of the Experimental Flamethrower Research Device which is inside the turret (center). This turret, which was set up specifically for this program, is of 1-inch armor plate set on a concrete pad; its purpose was to contain any possible fragments and/or fuel splash from an inadvertent malfunction, to protect both the adjacent instrumentation trailer and the nearby woods from possible fire, and to provide weather protection to the experimental setups. Initially both flamethrowers were fired from the machinegun tripod of the Flamethrower Research Device, which is fastened to the pad inside the turret. Later, however, it became necessary to move the solid propellant unit out of the turret, and a rigid pedestal was set in a new 4-ft x 10-ft concrete pad poured as an extension to the original support for the turret. This unit can be seen immediately to the right of the turret. The location of the solid propellant-actuated flamethrower is such that the instrumentation trailer is well sheltered from any malfunction by the adjacent wall of the turret.

Both the trailer and the turret are provided with ample electrical power for instrumentation, lighting, tools, and heat, and separate circuits are available to operate several high speed motion picture cameras.

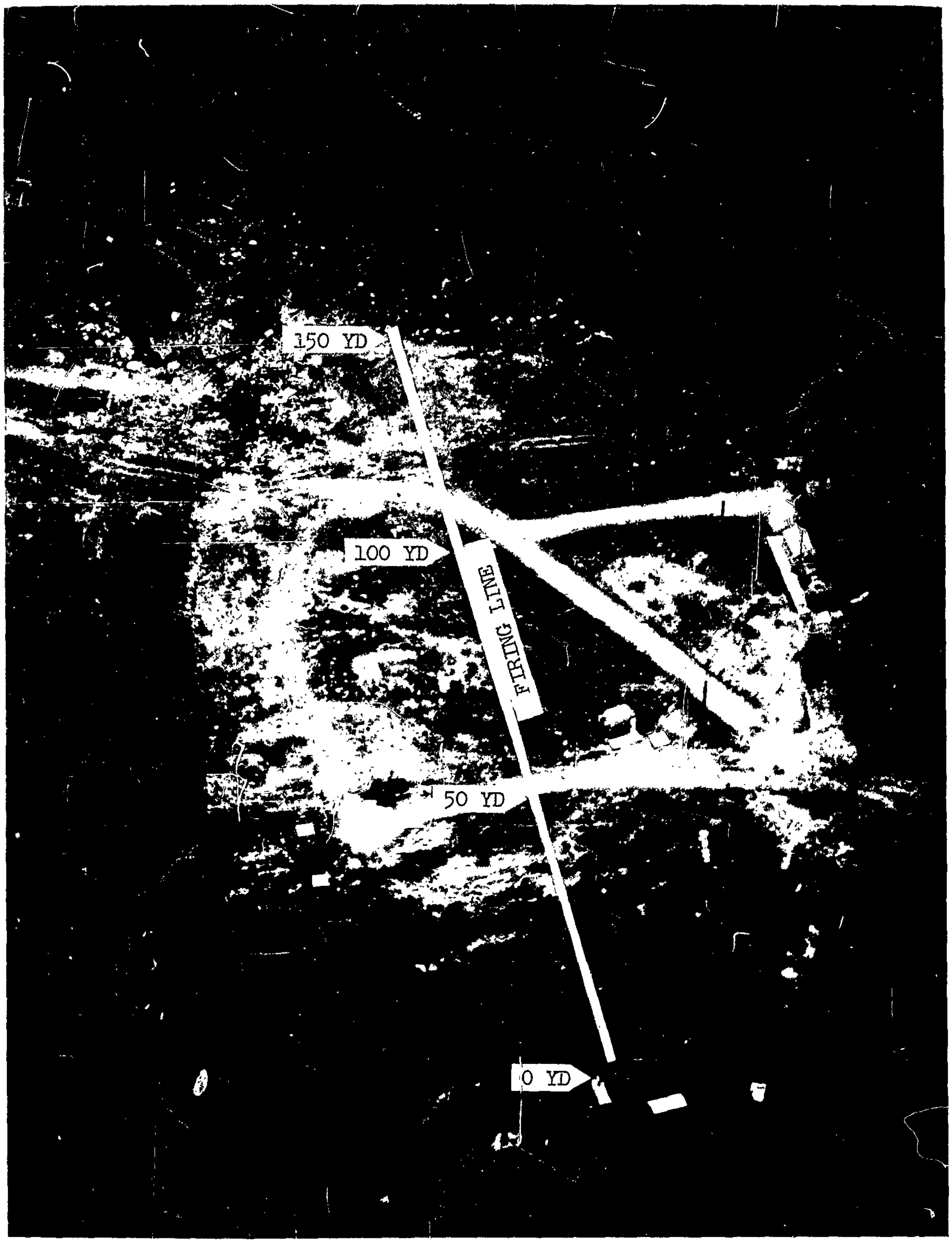


Figure 22 . Flame Weapons Test Range

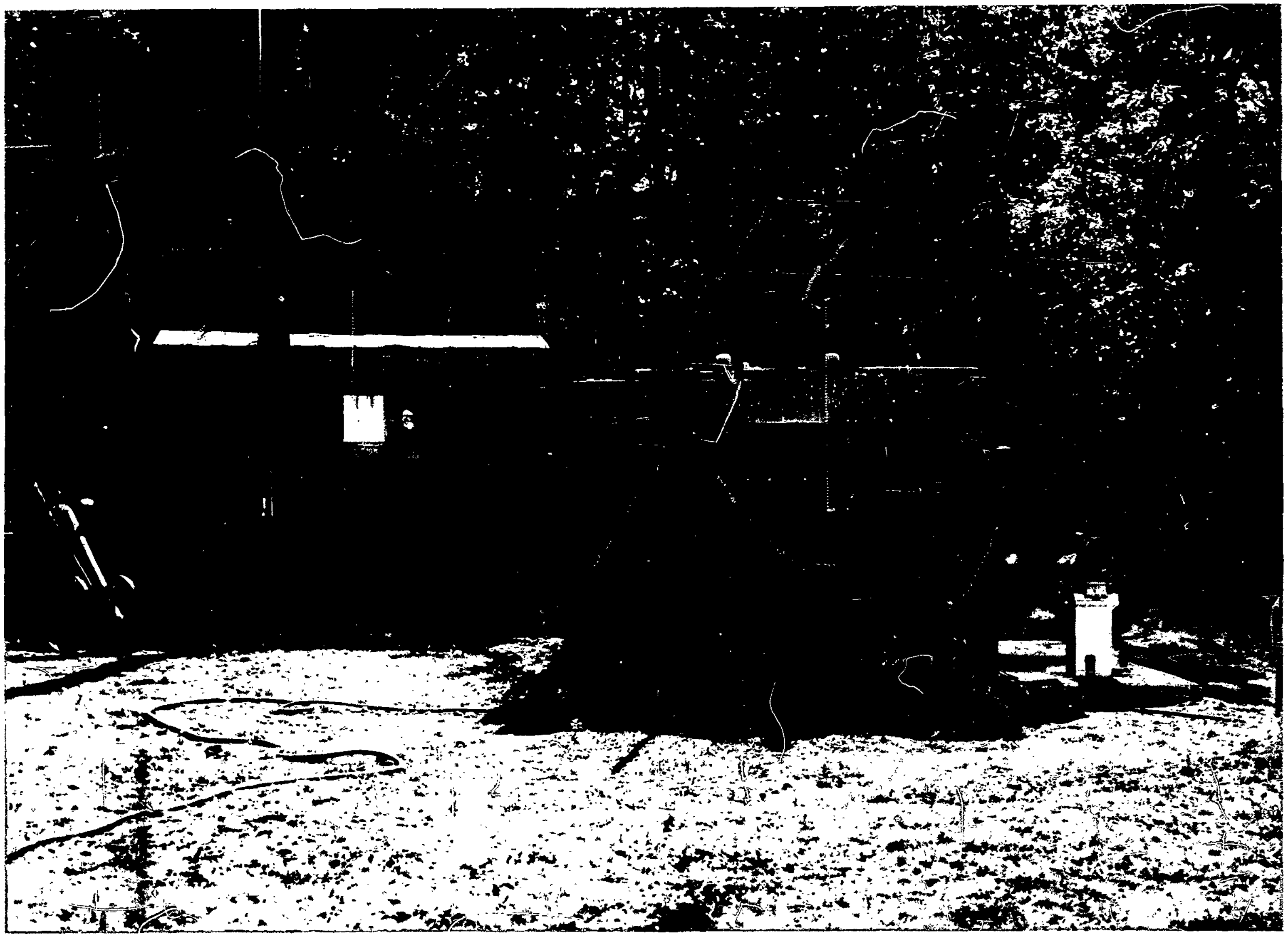


Figure 23. Flamethrower Firing Site

7.0 CONCLUSIONS

7.1 Liquid Propellant Approach

In the tests with the gas generator pressurization system individually and with the complete flamethrower system, it was demonstrated that the liquid propellant concept was feasible for providing long-range multi-burst capability. Specifically, it was shown with the bipropellant liquid flamethrower system that

--Two modes of gas generator operation are feasible for pressurization:
1. "minimum energy" pressurization only during expulsion, with variable pre-expulsion delays
2. "instant readiness" pressurization with no pre-expulsion delay

--recoil compensation is possible

--combustion processes can be properly controlled and synchronized for pressurization and recoil compensation

--a simple throttling hot-gas relief valve affords a non-electrical means of pressure control

--a liquid bipropellant combustor can generate relatively low-temperature gases for pressurization, and can be restarted reliably against a high backpressure

The feasibility of using combustion processes to actuate a multi-shot, long-range flamethrower composed of a man-held, recoil-compensated flame gun coupled by a flexible hose to a pressurized fuel tank has been successfully and clearly demonstrated. A ten-gallon flame fuel supply was concluded to be about the minimum which could provide at least a three-burst capability for a significant improvement over one-shot devices. A limited review of the significant components and fuel and propellant quantities of an operational multi-burst flamethrower of the type considered above indicated that overall loaded weight would be a minimum of 100-110 lb. As was recognized from the inception of the program, such a device would require two men, at the very least, to carry it; and even if mounted on a wheeled cart, probably still would require a two-man team. Consequently--and especially in view of the successful demonstration of a practical alternative (described in Section 7.2) subsequent to inception of this contract-- it was concluded that such a multi-shot flamethrower is not feasible as a man-portable combat device. Figure 24 shows one possible configuration for a 10-gallon unit.

It must be emphasized that this conclusion was based on very limited knowledge of battlefield considerations and no actual experience, and hence may be presumptuous. The using services may feel that sufficient justification for the multiple-shot capability (instead of multiple one-shot units) does in fact exist. In such an event, it has been definitely

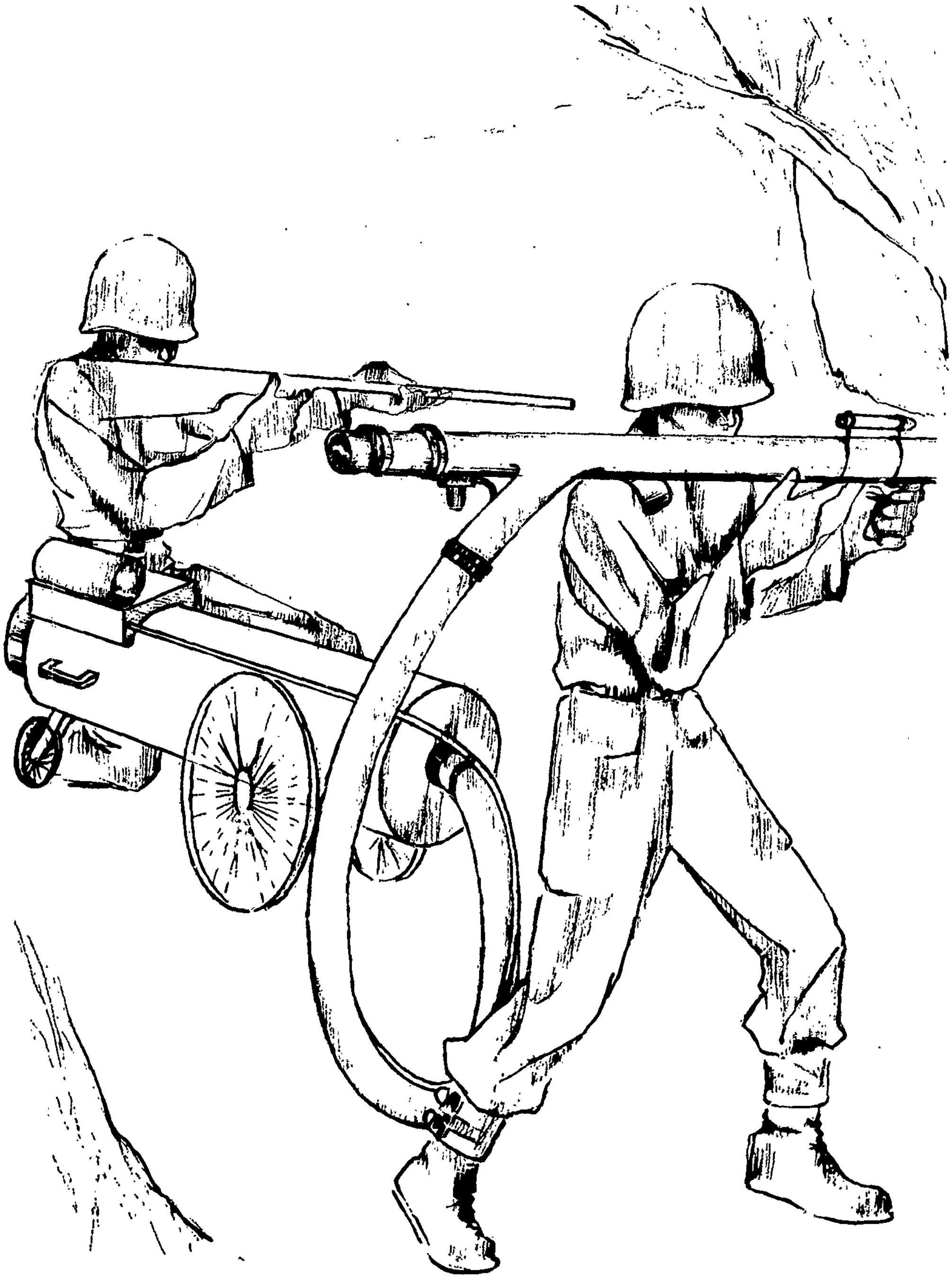


Figure 24. Artists' Conception of Possible Ten Gallon Long-Range Multi-Burst Flamethrower Configuration

established that the techniques developed in this program will contribute markedly to increased reliability and reduced weight over other means of pressurization and recoil compensation.

7.2 Solid Propellant System

The tests of the workhorse solid propellant-actuated flamethrower demonstrated that this concept can provide a simple, low-cost, lightweight recoil-compensated device capable of firing a single quantity of thickened fuel to ranges greatly in excess of those attainable with existing portable flamethrowers. Specifically, it was shown with the solid propellant flamethrower system that

--pressurization of a single-shot flamethrower with (cooled) solid propellant gases is feasible

--simultaneous rocket compensation of recoil and pressurized expulsion of flamethrower fuel by a single solid propellant grain is practical

--ignition of heavily-thickened flamethrower fuel by a small aluminized solid propellant grain is feasible, simple, and reliable

--initiation of the solid propellant fuel rod igniter grain simultaneously with the main solid propellant actuating grain can achieve fuel rod ignition

--the solid propellant fuel rod igniter can be used to provide a small rearward compensating impulse if required

Consideration of the number of shots fired from existing portable flamethrowers vs. their capacity, of the required fuel flowrates to attain long range, and of the probable rate of fuel burned in flight, suggested that a fuel capacity of 3 gallons (18.75 lb) might be nearly optimum for a one-shot flamethrower. Preliminary design of an operational model, together with vendor quotations, indicated that a large-quantity (100,000 to 1,000,000 units) production model could weigh 27-30 lb complete and cost appreciably less than $50 each, whether fabricated from steel, aluminum, or fiberglass-reinforced plastic.

7.3 General

The only significant operational deficiency of either system tested (and one which was not a responsibility under this contract) was fuel rod integrity at long range, i.e. concentrated area of fuel impact. The length of the area of deposit for a single expulsion represented 30% to 50% of the distance from the flamethrower to the farthest portion of fuel (generally 100 to 150 yards for the solid propellant unit), although the width of the

impact area generally was between 2 and 6 yards. It is considered that correction of this behavior will not be difficult, since the fuel rod from mechanized flamethrowers (which have operational ranges of ca. 200 yards) clearly remains intact for over 100 yards.

8.0 RECOMMENDATIONS

During the performance of this and prior contracts related to flamethrowers, RMD has developed a comprehensive background of experience and competence related to flamethrowers. Critical evaluation of the findings of this program, together with established capabilities in rocketry, combustion chamber development, and tank pressurization, and some limited analysis of postulated tactical considerations, have led to the following recommendations for proper utilization of the information developed under this contract:

8.1 Liquid Propellant System

1. Should a requirement exist for a multi-burst long-range recoil-compensated flamethrower, the following features are recommended for a prototype design: small, high pressure container of compressed gas regulated to pressurize propellant tanks; disposable cartridge-type pre-packaged propellant and gel tanks or inserts; and the "minimum energy" mode of operation. The gas generator valves should be battery operated while combustion products from the gas generator would supply pressurized gases for actuation of gel valve and CRR valves. A pressure switch or a hot gas relief valve would be used as a safety device to prevent overpressurization.

2. Liquid bipropellant gas generators of the type demonstrated on this program should be developed and substituted (including retro-fitting to existing weapons) for the flasks of compressed air which are used to pressurize mechanized flamethrowers. These flasks, as used on the M7A1-6 weapon in the M67A1 Flame Tank and the E31-36 AUV/APC Mechanized Flamethrower, are heavy, bulky, and expensive; but a much more serious disadvantage is that these systems are totally dependent upon the availability of field-type high-pressure air compressors. These compressors are heavy, bulky, and expensive, and require skilled operation and frequent maintenance. They require considerable periods of time to recharge the capacious reservoirs of mechanized flamethrowers.

It is possible to replace the large-volume high-pressure air storage system in these weapons with a liquid bipropellant combustion system of the type proven on this contract. This would afford a many-fold reduction in size and weight of the pressurization system, since the pressurizing gases are "stored" in the condensed phase as liquid propellants. Reloading of the propellant tanks should be by pre-packaged disposable containers, as described in this report.

3. Serious consideration should be given to the application of the liquid bipropellant gas generator to the dissemination of certain CW and/or BW agents. An instantaneous high flow rate of relatively low-temperature,

relatively non-reactive gases can be provided to form an aerosol with appropriate chemicals.

8.2 Solid Propellant System

1. Vigorous development of a prototype operational one-shot solid propellant-actuated recoil-compensated long-range flamethrower of the type described in the body of this report should be initiated immediately. This unit will meet or exceed essentially every characteristic of any improved flamethrower requirement which has come to the attention of RMD, with the sole exception of multiple-shot capability--and this is readily provided when required by firing additional units. Nearly every major function of the operational prototype described has been demonstrated successfully in the workhorse model; and those few functions which have not been proven all are well within the present state-of-the-art.

Development of this flamethrower would provide the infantry, Marines, and air assault troops with a highly flexible, mobile, compact weapon. It will greatly reduce the vulnerability of the operator, significantly increase his effectiveness, permit the use of flame against many targets now inaccessible--and accomplish all this with reduced weight and cost, and increased reliability.

2. Additional effort should be exerted immediately to determination of the modifications in fuel expulsion nozzle size and/or shape and consistency of the gelled fuel required in the workhorse solid propellant flamethrower to produce fuel rods which are essentially intact to ranges of 100 yards or more. Such rods have been obtained repeatedly from mechanized flamethrowers, hence are known to be attainable. There is good reason to believe that careful analysis of the differences between the systems, together with consultation with experts in the field of visco-elastic fuel rods, will lead to experiments which will produce a satisfactory solution to this problem.

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Earl C. Klaubert, Jack Kahrs
Final Report, 5 February 1964
103 pp, 24 illus, 11 tables
Contract DA 18-108-AMC-130(A)
DA 1C 522 301 A065 (4C-09-04-006)

UNCLASSIFIED

1. Chemical Warfare Equip. & Mtls.-Flamethrowers, Fuels & Combustion, Liquid Props, Solid Props.
2. Contract DA 18-108-AMC-130(A)

Work accomplished on the following phases is reported: (1) liquid prop.-actuated recoil-compensated exptl. flame-thrower: operating characteristics and transient matching of counter-recoil rocket, fuel rod behavior and range attained; (2) solid prop.-actuated recoil-compensated flame-thrower: aluminized solid prop. ignition, fuel rod behavior and range attained. Conclusions. Recommendations.

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